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Project Report

CORNING FILTER ONBOARD REGENERATION SYSTEM

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Abstract

The honeycomb ceramic diesel particulate filter (DPF) is currently the object of a great deal of attention in the search for means of substantially reducing particulate emissions from diesel engines. These emissions are mainly in the form of carbon soot and they are felt to pose a significant threat to human health. This is particularly true in underground mining operations where large sums of money are spent annually on ventilation and respiratory devices to combat the environmental effects of soot emitted from diesel equipment.

The effectiveness with which the ceramic DPF's collect soot is not in question. The technical issues now being addressed centre around the development of a practical ceramic DPF regeneration scheme and the associated hardware. Ceramic DPF's installed in a diesel exhaust system collect soot from the diesel exhaust until the right combination of inlet (to the DPF) gas temperatures and oxygen content is achieved to light-off and sustain regeneration. This regeneration is quite simply the burning off of the accumulated soot, and is required periodically to prevent plugging of the DPF. In several underground diesel engine applications, these conditions can be relied upon to occur naturally from time to time due to the load cycle of the engine. In many others, the load cycle is such that the high temperatures required for regeneration are not achieved under normal operation. For these, a separate system is required to induce those conditions.

This paper describes the design effort undertaken to develop just such a system. The initial requirements are documented and the evaluation criteria detailed. The design stages and steps leading to operating prototypes are chronicled. The result of this work is three operating prototypes, one suitable for use in a bay regeneration scheme, one suitable for use as a completely onboard regeneration system, and one whose merit has yet to be tested. This last design was rejected early in the process because of perceived risks, but events showed that those risks might be overstated. A prototype has been produced, though too late to be included in the testing process.

The paper goes on to suggest design principles to develop an optimal production version. This production version would be superior to any of the prototypes developed, in that the thermal inertia of the heater would be reduced substantially. The trade-off of conservatism in the present prototypes, for efficiency in the proposed, involves too many complex technical problems for present execution.

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1 Introduction

1.1 The Corning Filter

The diesel particulate filtering system to be regenerated uses a DPF made by Corning Glass Works. It was origionally developed as a substrate to support catalysts in automotive emission control. The product is an extruded ceramic (mainly cordierite), with cell passages running from end to end. By blocking the ends of alternate passages, the exhaust gases can be forced to pass through the porous material of the filter, with the ceramic acting as a particulate filtering media. This is in contrast to the current automotive use where exhaust gases enter and leave the same passages (catalysis rather than filtration).

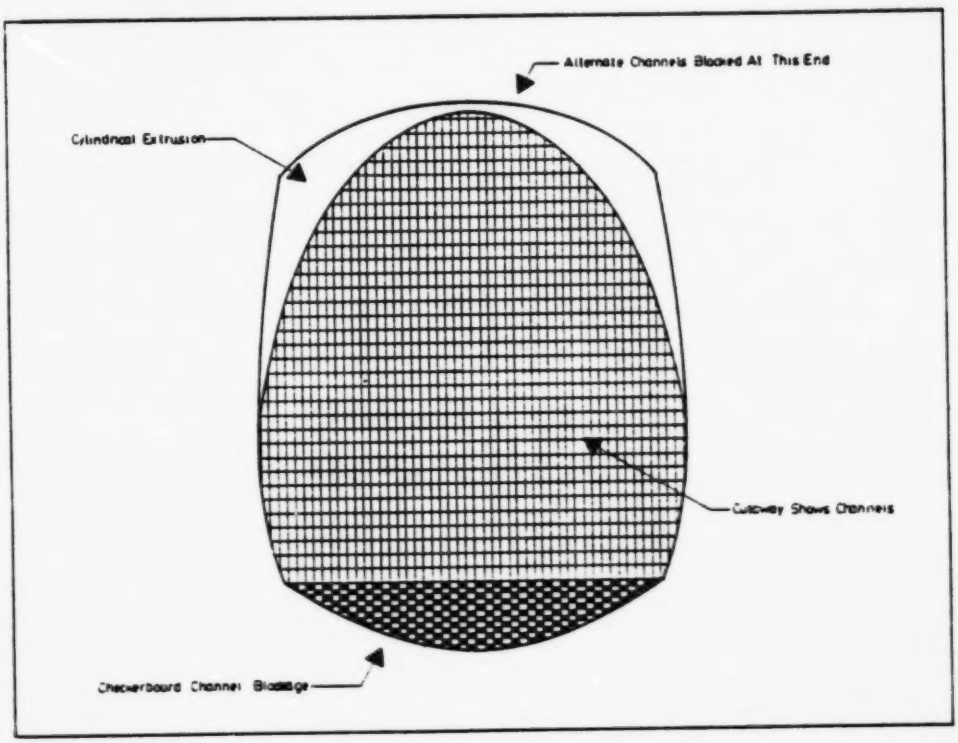

Figure 1.1 - A

Corning Filter Lattice

In particular, the Corning DPF considered in this project was assembled from individual sections of the basic honeycomb structure as Corning is not presently

capable of producing a single extrusion of large enough cross-section to handle the exhaust flows encountered in industrial diesel engines. The individual sections were bonded together to form a single, round, filtering unit which was canned for installation in the exhaust stream of a diesel engine. These DPF units had the following specification:

FILTER

Diameter: 11-3/8 in
Length: 12 in
Cell Size: 100 cells/sq in
Cell Wall Thickness: 0.017 in
Material Specification: Cordierite
Thermal Conductivity: 0.083 cal.cm/sq cm.s.deg C
Specific Heat: .292 cal/gm.deg C

CAN/HOUSING

Inside Diameter: 11-3/4 in
Wall Thickness: 12 ga.
Inlet/Outlet Cone Length: 4 in
Material Specification: 304L Stainless
Flange Type: Bolted Flange
Filter/Can Bonding Material: 3M Interam

Several such units were fabricated for CANMET and prepared for regeneration. The preparation consisted of installing them in the exhaust systems of operating engines till high levels of soot loading were induced. These units are shown in figure 1.1 - B, next page.

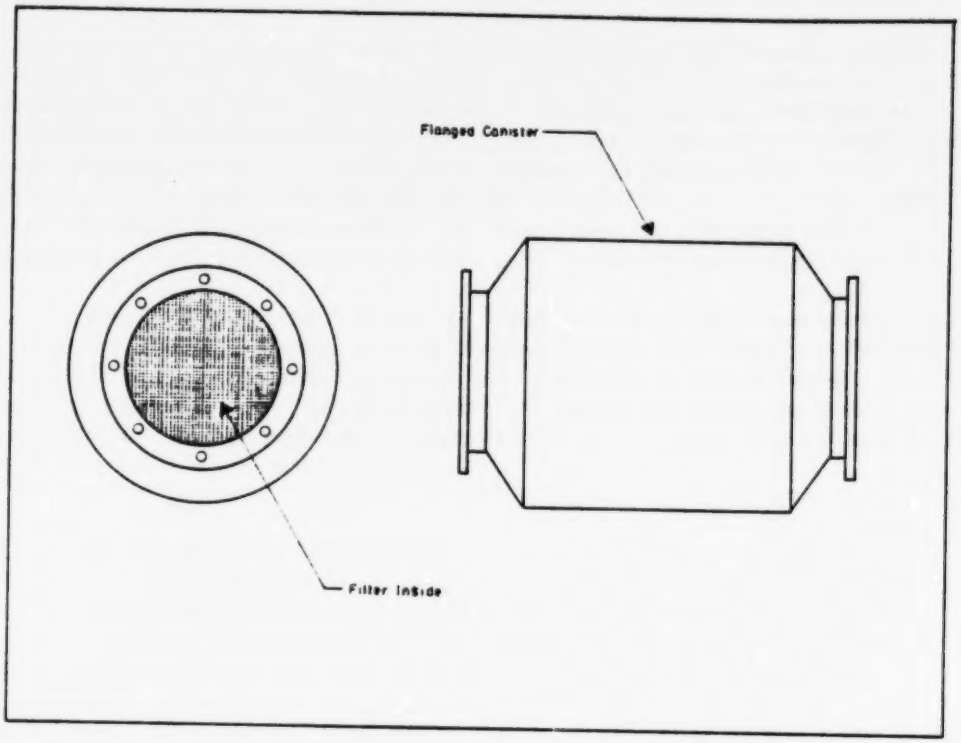

Figure 1.1 - B

Assembled and Packaged Corning Filter

1.2 Work Undertaken In This Project

This project was undertaken by Engine Control Systems Limited of Aurora under a contract let by the Department of Energy, Mines and Resources, through the Canadian Centre for Mineral and Energy Technology. The project was entitled "Corning Filter Onboard Regeneration System" and the basic requirement was to "design, construct and bench test an onboard exhaust filter regeneration system for application to dieselized underground machinery."

Previous studies performed by CANMET had shown the effectiveness of the Corning filter in reducing particulate emissions from underground dieselized equipment (1). In field testing, the filters had proven to be reasonably durable and the reductions in soot in the underground environment were clearly discernible. Industrial participants involved in the trials were enthusiastic about the filter's potential. The major technical obstruction to introduction of the filter appeared to be difficulties associated with its regeneration.

While the filter is in service on a diesel engine, more and more soot is deposited in its channels. The effect of this deposition is a buildup of soot which gradually comes to impede the exhaust gas flows through the filter to an intolerable extent. The back-pressures seen at the engine exhaust manifold could be detrimental to the engine's operation under such conditions. Depending on the machine's operating cycle, this buildup can occur within hours or weeks. At this point, the soot must be removed from the filter. The process by which this is done is called regeneration.

Regeneration is essentially the burning out of the mainly carbon soot from the filter's cellular passages. High enough temperatures (aproximately 950 deg. F) and the presence of oxygen will cause the soot to ignite and burn out of the filter. The soot is eliminated leaving only a residual amount of ash.

During the field trials mentioned above, regeneration was accomplished by the use of ovens. The filter unit was removed from the vehicle and placed in an oven where the required conditions for burning the soot were maintained and regeneration of the filter effected.

Another phenomena which was observed was "auto-regeneration." Certain vehicles, whose engines underwent a particularly rigorous operating cycle, appeared to require regeneration less frequently than others. It was determined that, during heavy load

cycles, the exhaust gas temperatures reached the ignition temperature of the soot. As there is always some amount of oxygen available in diesel exhaust, the filters regenerated spontaneously.

Nevertheless, this auto-regeneration would occur in a minority of actual mine vehicle/engine/cycle combinations and, as a rule, could not be relied on. The oven method of regeneration, on the other hand, was impractical as a day to day measure given the relatively short soot buildup time. It would require the frequent disassembly of the vehicle's exhaust system with too much labour and down-time involved.

It was decided that a simple, active, onboard regeneration system would have to be devised to bring Diesel Particulate Filtration to the underground environment. The development of such a system was the object of this project. Specifically, the goals were to:

1) "Conduct a conceptual engineering study of electrical and throttling regeneration options for ceramic filter cleaning without filter disassembly or removal, resulting in the selection of the better option...."

2) "Complete design drawings of the selected option...."

3) "Fabricate as necessary and assemble 3 regeneration units. Modify 3 filter units and assemble the regeneration units to the filters. Bench test the equipment to ensure adequate heating capacity and proper general functioning for each bank of a Deutz F8L413 engine."

1.3 Background Information

Diesel particulate reduction has been the object of a fairly extensive research effort in the past several years. The impetus behind this effort comes from the automotive industry, which is striving to meet new and stringent emission control requirements for diesel powered passenger cars. Our work could aptly be described as a spinoff of the overall effort.

Of key interest, in the question of particulate reduction, has been the concept of diesel particulate filtration as opposed to, say, processes involving continuous catalytically enhanced burning of particulate. Within the group of filtration devices proposed, the Corning ceramic filter has generated a great deal of interest. Much of the work done in this field has addressed itself specifically to the use of this or similar devices in the diesel engine exhaust system. This work can be broken down into three classes:

1) Health and economic aspects.

2) Regeneration performance data.

3) Regeneration control schemes.

Under the first category, "health and economic aspects," the work by Urban et al. (11) addressed itself to a comparative evaluation of various particulate control methods. Methods evaluated included alternate fuels and fuel doping, engine and operational modifications, and particulate traps or filters: metal mesh, ceramic foam or monolithic ceramic honeycomb. Of the techniques examined, trapping or filtration was found to be the most effective and, of the devices of this type available, the ceramic monolith was found to give the highest filtration efficiency. It was determined that this trap reduced total exhaust particulates by 90% and organic extractables by aproximately 75%. Loss of control during trap regeneration was cited as a significant problem, though the traps were found to be generally durable. A second study by Miller et al. (8) was a major effort aimed at detailing the performance of the Corning filter as an emission control device. Major conclusions of this study were that solid particulates are filtered at up to 94% filtration efficiency, but that this efficiency can vary with engine load and speed, falling to as low as 35% at intermediate speed and 25% full load. This is due to the variation in particle size with varying

engine speed and load.

Most of the economic data available were relevant to the automotive industry and indicated a high cost/benefit ratio. The economic considerations in the mining industry would be different. The work of Howitt et al. (6) addresses itself to mine economics. Using an argument based on the reduction of ventilation, with correspondingly reduced power, maintenance, heating, and capital costs, their study would appear to indicate good economy for the use of the Corning trap, or like device, underground.

Under "regeneration performance data," two works were found to be of benefit. The first of these was that by Gulati (3). This was primarily a theoretical treatment of the problem of thermal transients and the resulting stress and strain within the Corning filter monolith during regeneration. The second, by Higuchi et al. (4), was an empirical treatment of the same subject based on a similar type of filter manufactured by NGK Insulators. Both of these studies pointed out difficulties with hot zones and thermal gradients during the regeneration process. The latter related the performance of the filter to the inlet gas temperatures, the oxygen content of the inlet gases and the flow rate of these gases as well as a range of combinations of those three parameters.

Finally, three studies looked directly at regeneration control schemes. In two studies by Wade et al. (12,13), active methods of inducing and controlling regeneration were considered. The earlier of these (12) was basically a general consideration of the problem, with several techniques being covered. These included high speed/high load engine operation, throttling, catalysis, fuel doping and an in-line burner. The second work (13) expanded on the in-line burner concept as it had been the most promising of the earlier investigated options. The major conclusions of the second study were that, though the in-line burner was effective in inducing regeneration, problems remained with burner clogging, burner ignition reliability, trap durability due to regeneration runaway, and control system complexity. The work by Oser (7) was primarily a survey of techniques already discussed.

2 Technical Discussion

2.1 Prototype I

2.1.1 Preliminary Concept Evaluation

The basic requirement for any onboard DPF regeneration system is the attainability of soot ignition temperatures within the filter itself. This requires heat introduction from an external source as the engine's waste heat is not generally sufficient to achieve such temperatures in the raw exhaust gases. A brief survey of all possible sources was conducted and an electrical, battery powered configuration was confirmed as the most favourable from the points of view of simplicity, reliability and portability.

Two means for applying electric heat were considered. One of these was direct and entailed installing heating elements either right in the ceramic filter lattice or in close proximity to the filter's leading edge. The other had a separate heating package being developed. This would be placed upstream of the filter, with its elements heating the exhaust gases prior to their entering the filter.

The advantage of the former concept was its direct heat transfer mode; radiant to the filter. It was reasoned that this technique would cause ignition in small zones of the filter, and the exotherm thereby produced would spread and sustain the regeneration. This would be far more energy effective than the latter proposal. The advantage of the latter was that, though there would be a much larger power requirement to heat all the exhaust gases to the ignition temperature of the soot, the problem of thermal shock inherent in the first option would be alleviated. In consultation with the filter's manufacturer, the gas heating option was chosen over the direct filter heating one. It was felt that the benefit of safety against thermal shock outweighed the penalty of a much greater power requirement.

The raw exhaust gas temperatures and flow rate encountered during regeneration determined the power requirement for the heater.

Exhaust gas temperatures for the Deutz F6L 912 W engine, the one actually used in this prototyping, can range from about 320 deg F at a low-speed idle, to temperatures well in excess of the 950 deg F soot ignition temperature under conditions of high-load and high-speed engine operation. Practically though, whatever regeneration system was designed would have to be applied to a wide range of vehicles

employing the same engine. Some of those vehicles would rarely see service where the exhaust gases would be much hotter than those of an idling engine. A legitimate design constraint was that the system be able to raise the exhaust gas temperature all the way from that of an idling engine to the 950 deg F required for the ignition of the soot.

With increasing engine speed, the exhaust gas flow rate and the power required of the heater to achieve that temperature rise increases. At the time that this design was evolving, there was little design data to suggest any particular gas flow rate as being optimal for regeneration in a filter of the geometry used here. What data there was (3), related to specific filter geometries and gas conditions, and was not generalized sufficiently to form a basis for a design decision in our case. In general, caution against too low a flow rate for good divergence of gas flows in the filter was advised. On the other hand, the high oxygen content of exhaust gases coming from an idling engine (up to 18%) seemed a good reason to avoid high flow rates in order to avoid the possibility of a regeneration runaway. In the absence of more specific information, it was decided to design for a regeneration process taking place at a mid-range flow rate (ie., a mid-range engine speed). This would leave some room for adjustment either way in actual operation.

Based on an engine speed of 1500 rpm, the exhaust gas flow rate of an idling F6L 912 W engine would be roughly 715 lb/h. Without any loading of the engine, the gas temperature would not be much greater than 350 deg F. The heat input rate needed to raise that gas to the 950 deg F level would be about 100 MBtu/h. Electrically, that load would be about 30 kW.

Our foremost consideration was the notion of having a completely self-contained unit which would be battery powered. On consultation with several battery manufacturers, it was realized that a 30 kW power requirement was going to mean a very large and expensive deep-cycle industrial battery. Safe operation at that power would have required a unit costing almost $5000 and weighing almost 3000 lb. We had previously evaluated rough size, weight and cost limitations for the entire system and such a battery would certainly not fit that picture. A practical unit for such a mobile installation could not exceed 1500 lb and a cost of $2500. 17 kW was the advised power limit on an industrial deep-cycle battery in that weight and price class. The design constraint of 17 kW was introduced to the problem. That is, the heater unit could be designed for no more than 17 kW input. Other means of raising the temperature of the exhaust gases to 950 deg F would

have to be sought to complement the heater.

The solution to this problem was thought to be found in the manipulation of the engine's operation during the regenerative process. Several means of artificially producing elevated exhaust gas temperatures (over those of a normal idling engine) were considered.

One of these involved loading the engine against the vehicle's torque converter with the wheels locked, thus artificially simulating a high load condition. This technique raised the spectre of burned out torque converters and voided warranties so it was not given further consideration.

Theoretically, another way of inducing a load condition, and thus elevating exhaust gas temperatures, would be to load the engine dynamically, that is, run the engine through a hard acceleration cycle at the point where heat augmentation is most desireable. This should result in increased exhaust gas temperatures, at least for a short time. It was decided to attempt to employ this phenomenon.

The last means considered was that of throttling the engine's air flow during the regeneration. By this measure, the air flow would be reduced, giving a higher fuel/air ratio than normal. As less air would be available to carry away the heat produced in burning the same amount of fuel, the exhaust gas temperatures would be higher than normal. Another benefit of this procedure would be the reduction of oxygen levels in the exhaust gases. This would add a degree of control to the regeneration.

The inclusion of dynamic loading and throttling into the regeneration scheme presented a complication in the control strategy. With a simple heater of sufficient power, control would be no more than "on/off" with appropriate overrides and interlocks, etc. The notion of using dynamic loading and throttling would involve a decidedly more complicated control system than had previously been contemplated. Such complicated control algorithms could not be left to the vehicle operator.

A feedback control system was envisioned for the system. Its operation would be completely transparent to the operator, his only contribution being to engage the system. The strategy was to have the engine speed initially set to the nominal 1500 rpm. Upon engagement of the regeneration control system, the heater unit would immediately be set to full power. Simultaneously, the control system would thrust the fuel rack to the

maximum fuel flow and throttle the engine to some preset level. The onset of regeneration would be sensed by a pair of thermocouples detecting a temperature rise across the filter. At this point, the heating unit would be returned to a much lower power setting to maintain regeneration (it was thought that the flame propagation rate within the filter might not be sufficient to maintain the regeneration without some preheating of the raw exhaust gases) and the fuel flow rate would be reduced to a level giving controlled regeneration (by exhaust gas flow modulation). A single throttling position would remain in effect throughout the process to ensure safe oxygen levels in the exhaust gas at all times. A block diagram of the control system is shown in figure 2.1 - A.

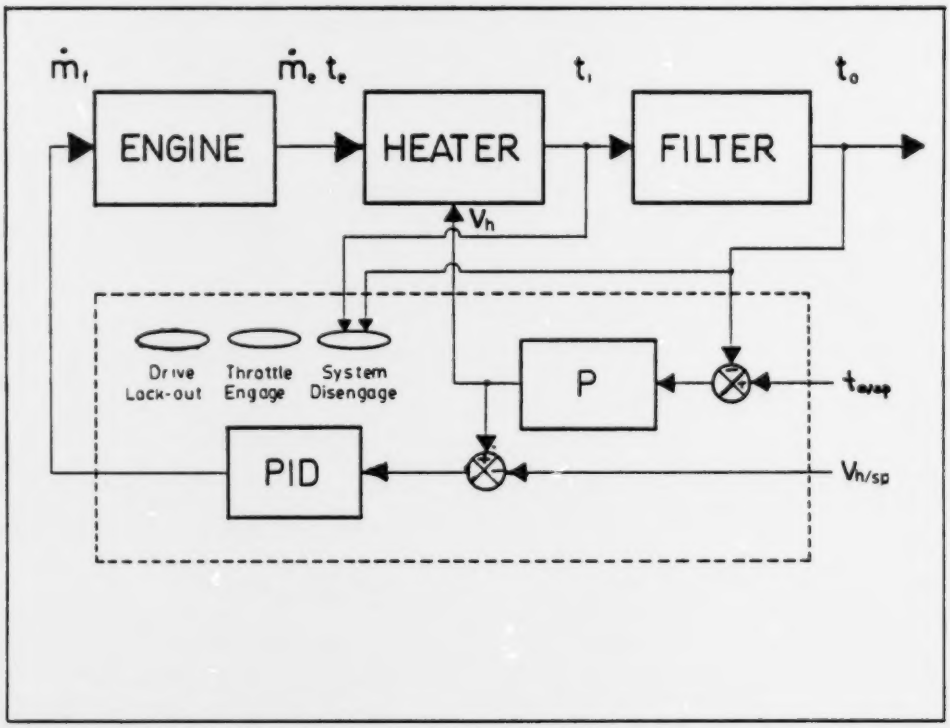

Figure 2.1 - A

Block Diagram of First Prototype Control System

The main components of the conceived system would be the 17 kW heater unit, the filter, the solid state continuous controller and sequencer, and a large battery. Such a system could be built onto each vehicle

and, with the possible exception of the battery, the developed components would have a fairly low cost in production.

The controller itself would consist of the major continuous control loops as well as supplementary circuitry for system sequencing. The drive lock-out would be on from the time the regeneration control system was engaged to the time it was disengaged. This would also hold true for the throttle engage. Each of these signals would drive electromechanical devices to take the appropriate action within the vehicles existing controls. Logic circuitry in the "system disengage" unit would sense a series of states (signals from the thermocouples located before and after the filter itself) in the regeneration process. Three states would be anticipated. The first of these would be the pre-regeneration state. In this state, the filter inlet temperature would exceed the filter outlet temperature because there would be heat loss within the filter, but no exotherm would have yet been achieved. The second state would be the regeneration state, typified by a higher filter outlet temperature than inlet due to the exothermy of regeneration. The third state would be the post regeneration state, one similar to the first in that the filter inlet temperature would exceed the filter outlet temperature due to the loss of the regeneration exotherm. Upon sensing the third state, only after having seen the first two, the system disengage would disconnect the control system and return the engine to normal operation.

The heart of the control system would be the proportional control loop modulating the heater voltage (and hence, power, current, and heat input) and the cascaded proportional, integral and differential control loop modulating the fuel flow (and hence, exhaust gas flows and, under transient conditions, raw exhaust temperatures). Upon engagement of the control system, a large positive error between the measured filter outlet temperature and the set-point for this parameter would immediately cause the heater element to be thrown to full power. At the same time, the higher heater voltage signal would cause a large positive error between itself and its set-point value in the cascaded loop. The PID controller would then throw the fuel rack to the maximum flow rate to accelerate the engine as quickly as possible, producing elevated temperatures in the raw exhaust gases and assisting the heater in achieving the 950 deg F filter inlet temperature required for regeneration to commence. Once the regeneration had been induced, the outlet temperature of the filter would rise dramatically and the heater control loop would respond by reducing the voltage across the heater. That, in turn, would cause a

return of the fuel rack to the origional setting. From then, till the regeneration was complete, both the heater unit's voltage and the engine's fuel flow would be continuously controlled to maintain an even regeneration of the filter.

2.1.2 The First Prototype Implemented

Upon consideration, it was decided to test some of the principles upon which the first concept was based. Though the solid state controller would not be expensive in production, its development would be a relatively ambitious undertaking. Similarly, an industrial battery was an expensive aquisition whose future usefulness hinged too much on the success of the scheme as a whole. It was decided to actually test the viability of using engine throttling and dynamic loading to augment the heat input of the heater unit. The control strategy would be tested by manual manipulation of the engine throttling and fuel settings, and the heater would be designed for 220 v ac operation (a readilly available source in the lab) rather than dc. Nonetheless, the power rating of the heater would be equivalent to that foreseen in a production dc version.

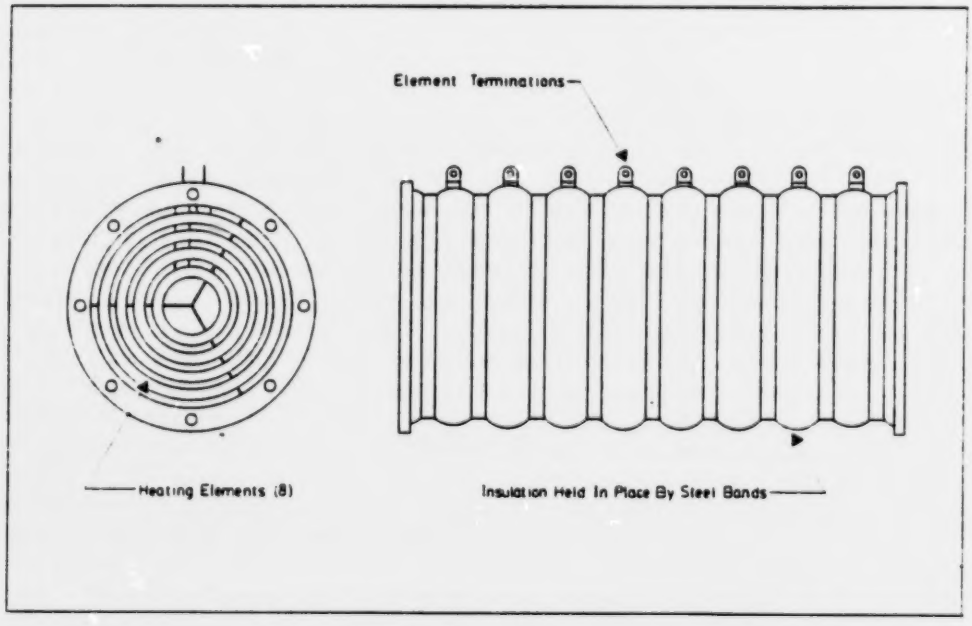

Figure 2.1 - B

Regeneration Heater - Prototype I

The heater was designed to be geometrically similar to its future dc equivalent. Heating elements were secured which, though 220 v rated, could be duplicated in a dc design with the same watt density on an equal surface area.

The actual heater is shown in Figure 2.1 - B. The 7 inch I.D. shell was manufactured of 16 ga. stainless 304 sheet. Flanges at either end of the shell secured the heater to the exhaust system. The shell itself was insulated by a 1 inch layer of Fibrafax insulation.

The heater elements, of which there were eight (at 1500 W each), were of the coil type (top-heaters), with 4 turns and an outside diameter of 6 in. The sheath diameter of the elements was .440 in. The elements were equispaced down the shell of the unit at 2 inch intervals (the shell is 19 inches long overall). Mounting of the coils was aranged by using a tri-armed support, tack welded to the downstream face of each element. The ends of the support were welded to the shell. The terminations of each element protruded through holes in the shell to the electrical connections.

Control of the unit was by having groups of elements connected to the power source through relays. By switching in a given combination of elements, the power input could be modulated in discrete steps. This was really the only distinction between the prototype and a production unit. The production unit would have a continuously variable power input. The deviation was allowed because an SCR controller would have had to be designed or obtained at some cost while the relays were in our posession. In as much as the ultimate goal was to produce a dc unit, the SCR controller would not have had any ongoing value.

The device was fabricated as shown and installed in the exhaust system of the F6L 912 W engine used for the prototyping. A previously loaded Corning filter unit was also installed in preparation for the trials of this concept.

2.1.3 Test Results - The First Prototype

In the testing of this concept, it became quite clear that the sophisticated controls approach was not going to work. No perceptible exhaust gas temperature rise was obtained from either dynamic loading of the engine or from throttling. With the clarity of hindsight, the reasons for both of these failures can be seen.

In the case of dynamic loading, the explanation was in the thermal inertia of the engine block and exhaust system. Even under a suddenly applied shaft load, it would take some time before a significant temperature rise was seen in the exhaust gases: this despite the fact that the cylinder temperature would increase almost immediately. The mass of the engine and exhaust system is a very large heat sink. Much of the extra heat produced would be absorbed until the engine had stabilized at the new operating temperature. Dynamic loading would produce an immediate increase in cylinder temperature, but the dynamic loading can only be sustained for a few seconds till the engine reaches maximum speed. This is not enough time to overcome the thermal inertia of the engine and exhaust system. No useful temperature augmentation of the exhaust gases will occur during such a short period.

The failure of throttling to produce a temperature rise was a bit more surprising, but this too can be explained. What actually happened in the testing was that, as soon as the throttling valve was closed sufficiently to affect the air flow, the engine stalled. This is because throttling increases the pumping work which must be done by an engine. This increase in pumping work must be compensated for by an increase in fuel flow or the engine will slow down. In the case of an idling engine, the pumping work is the major component of work being done, and small changes in throttle setting, without fuel compensation, will stall the engine completely. Provision had not been made for automatic fuel flow compensation, nor realistically could it be.

The failure of the dynamic loading and throttling concepts to aid in achieving the needed temperature rise really meant the failure of the entire concept. Without these heat augmentation measures, the heater itself was hopelessly underpowered to acheve the temperature rise required for regeneration.

Nevertheless, the heater unit was tested. Under an applied 220 v, the current flow was as planned, giving a 12 kW power consumption in the heater. Heat transfer to the gases was 80 % effective giving a temperature

rise due to the heater's action of about 190 deg F. The 20 % of the power not imparted to the gases is assumed to have been lost from the unit's casing. The magnitude of this loss was noted for consideration in subsequent designs.

2.2 The Second Prototype

2.2.1 Concept Re-evaluation

The results of testing done on the first prototype showed conclusively that the electric heating unit would have to achieve the entire temperature rise by itself. Engine throttling and dynamic loading would not make a contribution. As well, these tests had yielded some intimation of the heat transfer efficiency of such an electrical heater configuration, roughly 80%.

About the time that this re-evaluation was taking place, new information was brought to our attention. This was the result of experiments performed independently at CANMET. During an experiment done to characterize the regeneration process itself, it had been discovered that there was a criterion which could be used to ensure safe regeneration at high exhaust gas oxygen content and low exhaust gas flow.

The experiment had been designed to use auto-regeneration (by loading the engine on a dynomometer) to obtain general regeneration characterization data. During the test, a runaway condition was encountered: the CO reading down stream of the filter went off scale. The conventional wisdom, in such a circumstance, would be to increase the exhaust gas flows. This would be to gain the extra heat dissipation of a high gas flow. On the other hand, a more intuitive response would be to reduce the flow rate to starve the combustion in the filter.

In fact, the intuitive reaction was taken. The engine was slowed to a low speed (700 rpm) idle. The regeneration process returned to a thermally stable state and continued under complete control until all the soot was removed from the filter. This was with the very high exhaust gas oxygen content and low exhaust gas flow rate and temperature of an engine operating at a low speed idle.

Upon disassembly of the rig, and examination of the filter, there was no apparent damage to the ceramic.

The implication of this was that the entire on-board regeneration system could be specified to operate at the lowest possible exhaust gas flow rate available from the engine, that of a low speed idle. Moreover, once regeneration had been induced, there would be no further need for pre-heating the exhaust gases to 950 deg F; the flame propagation rate in the filter would be sufficient, even with cool inlet gases, to maintain the regeneration. The heater could be turned off as

soon as ignition had been achieved within the filter. This would mean that the power pack would have to operate for a shorter period than anticipated. The current draw for a given battery might be increased over that which could be considered for a sequence of longer duration.

The filter back pressures measured during the experiment were significant. Back pressure has been shown to be a good indicator of the soot loading of a filter. This is because, as the filter's soot load grows, the congestion of its passages increases. This impedes the exhaust gas flow more and more. As this impedance grows, the pressure drop across the filter increases. Pressure drop across the filter is a function of gas flow rate and soot loading. The nature of that relationship has not yet been fully characterized, but, from the data available, such a relationship does appear to be experimentally repeatable.

At the point where the action to regain control of the runaway regeneration was taken, the back pressure across the filter was recorded as 20 inches of water. The actual exhaust gas flow was not recorded, but the engine had been operating at 2200 rpm with 200 ft.lb of torque on the shaft. The conclusion drawn from this was that the soot load which gave rise to that back pressure represented a level at which safe and stable regeneration could take place at a low speed idle.

This criteria was standarized by adopting 2200 rpm and 150 ft.lb torque as the standard operating condition at which the back pressure should be measured. When the back pressure reached that level, at that operating condition, the filter was ready for safe regeneration.

With these considerations in mind, it was decided to proceed directly to a fully battery powered system. With the actual observation that regeneration would continue once started, even when the exhaust gases entering the filter were cool, the duration of the heater's operation could be reduced. This would ease the specification of a reasonably sized and priced battery. A battery's rating is a combination of rated current and rated time of discharge. A reduction in the time of discharge would allow an increase maximum discharge rate.

2.2.2 The Second Prototype Implemented

The second prototype is shown in figure 2.2 - A. Note that the inlet and exhaust ports were located on the shell rather than at the end of the unit. Also, straight rods were used in place of the coil type heating elements.

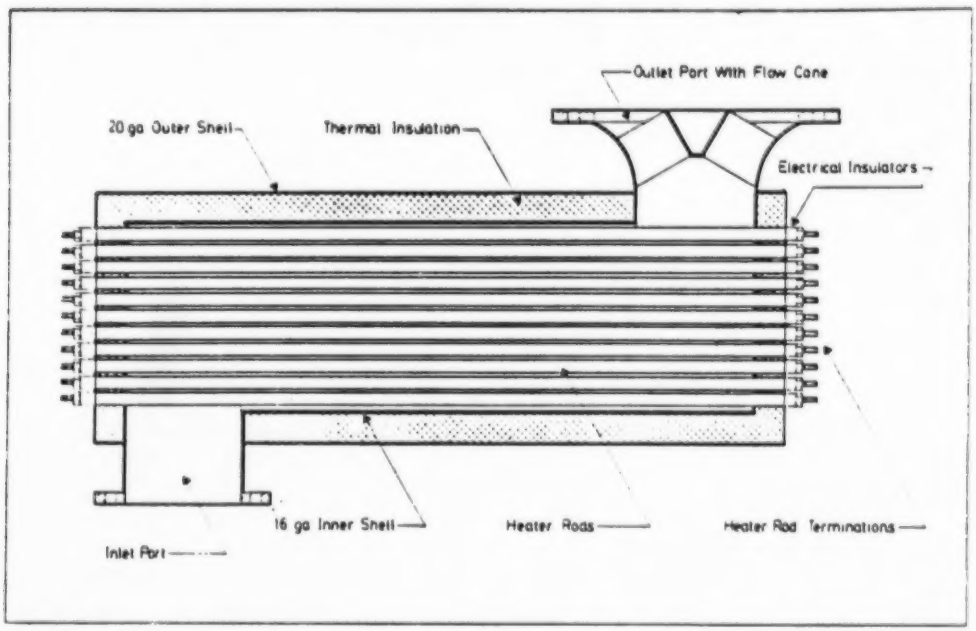

Figure 2.2 - A

Regeneration Heater - Prototype II

The second prototype was sized for the heat input required to raise 400 lb/h of 320 deg F exhaust gas to 950 deg F. The figures of 400 lb/h and 320 deg F were considered typical of a Deutz F6L 912 W engine at a low-speed idle of 700 rpm (manufacturer's figures). The required power input was calculated to be 17.7 kW. In consideration of the 80% efficiency of the first prototype, and the desireability of maintaining some margin of power, that rating was increased to 24 kW.

The information received from CANMET, which had shown that the heater could be turned off as soon as regeneration had begun, changed our perspective on

batteries. Whereas we had only been considering industrial deep-cycle batteries to this point, the shorter anticipated time of discharge allowed a relaxation of that specification. Inexpensive automotive type batteries could, in the right combination, provide the type of current draws which would be necessary.

The criteria for system voltage was that it be as high as possible without being potentially hazardous to the operator in any point of the system. The higher the voltage, the lower the current would have to be to achieve the rated power. The lower the current was, the lower would be the losses in the supply cables, and the smaller those cables could be. On the other hand, 24 volts, or two 12 volt automotive batteries in series, would be about the maximum safe voltage which could be used while still avoiding the risk of shock. Thus, 24 volts was selected as the system voltage.

At 24 volts, the current needed for 24 kW was 1000 amps. Neglecting voltage drop in the supply cables, the overall resistance of the heater unit was specified as .024 ohms. When that specification was presented to the manufacturer of the heating elements, it was revealed that, to get such a low overall resistance and still maintain reasonable conductor temperatures, the conductors within the heating rod would have to be spiralled rather than straight. At the time, production difficulties prevented the incorporation of this in a coil. The heating elements would have to be straight rods.

The rods produced are shown in figure 2.2 - B. The essential features of this rod are its Incalloy 800 sheath, the granular Magnesium Oxide packing within the sheath and the spiral wound conductor at the centre. The exact physical description of the conductor is considered proprietary by the manufacturer.

The actual heat zone of the rod is only 12 inches long. This was accomplished by restricting the spiral of the conductor to that particular section (increasing the watt density within the section). Each of the rods is rated at 22.5 amps with 24 volts across it. This gave a watt density at the surface of the sheath of 32.6 watts/square inch.

There were 45 of these rods in the second regeneration heater, with a total power of a little more than 24 kW. The rods were grouped in banks of 9 for the purpose of power distribution, each bank contributing one fifth of the total power. Each of these banks was controlled by its own relay.

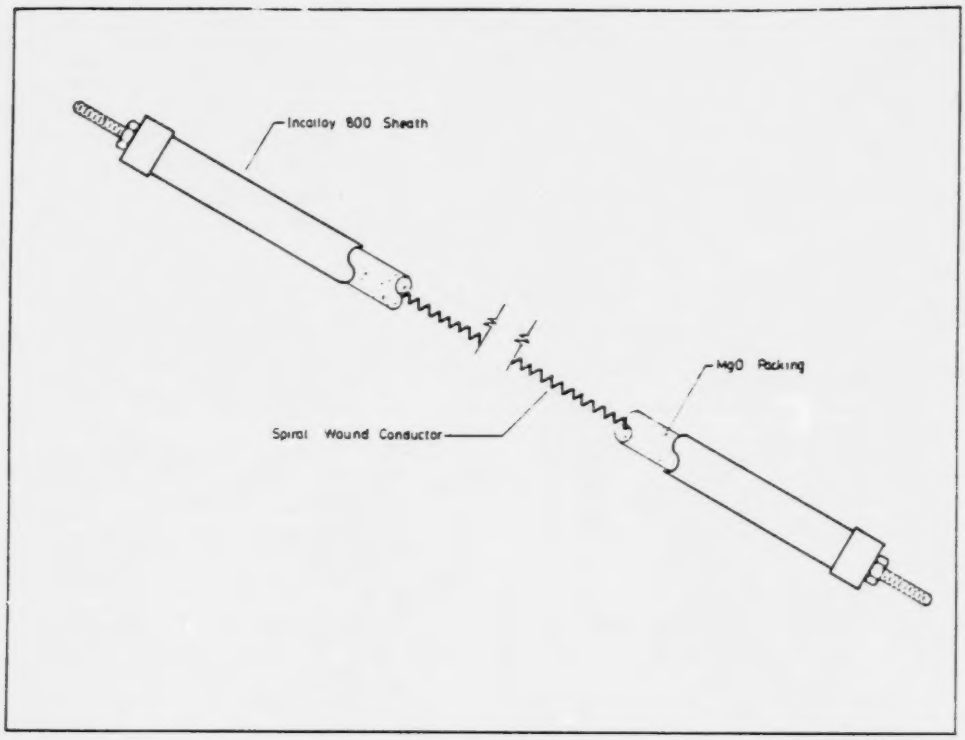

Figure 2.2 - B

Heater Rods - Prototype II

The use of these straight rods forced us to look at a somewhat different configuration for the heater. The inlet and outlet ports were placed on the sides of the heater rather than the ends. This allowed the convenient termination of the rods on the heater's end plates. It is felt that this configuration will also reduce the overall space requirement for the Diesel Particulate Filtration system on the vehicle; this by allowing more flexibility of installation.

To supply the power for the system, four off-the-shelf truck batteries were wired together. Each of these batteries had the following specification:

Battery Specification

Number of Plates: 138
Voltage: 12 Volts
Minimum Reserve Capacity @ 25 amp draw: 310 minutes
Minimum Cranking Amps @ 0 deg F: 800 amps

This specification is obviously geared more to automotive starting applications, but, unfortunately, is the only information available, even from the manufacturer. After 30 seconds at 800 amps, the battery should maintain a cell voltage of 1.2 volts. After 310 minutes at 25 amps, it should maintain a cell voltage of 1.75 volts. The batteries were connected into a single 24 volt power pack by series connecting two pairs of batteries and then connecting those two battery pairs, in parallel, to a single pair of supply leads.

2.2.3 Test Results - The Second Prototype

The second prototype system underwent a series of tests in the CANMET diesel engine test cell. Several identical filters had been prepared for the testing by running the engine through simulated vehicle load cycles on the dynomometer. The test set-up was generally as shown in figure 2.2 - C, though certain minor changes were made for particular tests.

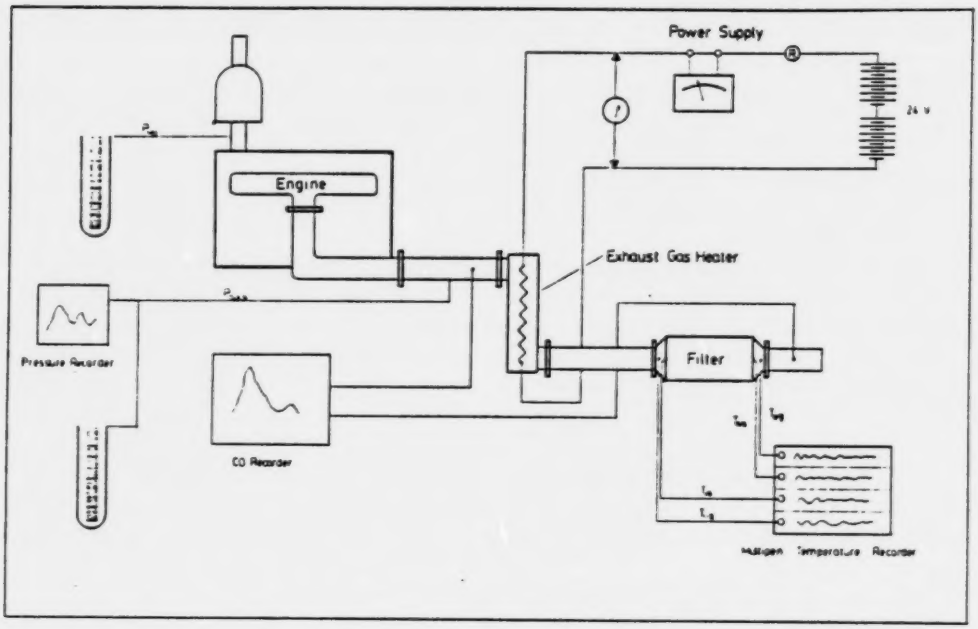

Figure 2.2 - C

Test Set-Up - Prototype II

The first test done was to establish that the heater met its electrical specifications and that its rated power was sufficient to induce regeneration under the prescribed engine operating condition; a low-speed idle. It was decided to preserve the batteries in factory condition for the more critical testing to come; that of the system with a filter carefully loaded to exactly the design level of soot loading determined in the earlier regeneration tests by CANMET.

For the first test, welding machines were used as a power supply for the heater. Four welding machines were rented, three of which were rated at 300 amps and the fourth at 400 amps. Each of the 300 amp machines was circuited to one bank of elements. The 400 amp machine was connected to two banks. Each of these four power circuits was controlled by its own relay, switched from the control room.

As welding machines are electrical voltage sources (the voltage is automatically controlled to deliver a specified current whatever the load), it took a certain amount of adjustment to set them to deliver the required 24 V to the heater rods. Each circuit was dealt with in turn, and the welder's current selector adjusted manually until 24 V was measured across the elements in the connected bank(s). The engine was run during this operation to ensure that the rods did not burn out. All other banks than the one being set were switched off to ensure that regeneration was not inadvertently induced during the test set-up. Once the desired voltage was reached, the current selector was fixed and not adjusted for the duration of the test. Just prior to the actual test, the following currents were measured in each power circuit:

Current In Heater Banks @ 24 V

Second Prototype

Bank 1.....200 amps

Bank 2.....200 amps

Bank 3.....200 amps

Banks 4 & 5.....420 amps

The current values measured were within a good design tolerance, giving a total input power of about 25 kW (1020 amps @ 24 V), slightly more than specified.

After checking the heater's operation, the soot loading of the filter in use was checked. The engine was set at 2200 rpm and 150 ft-lb torque using the dynomometer. That setting, it will be recalled, is the condition at which the soot loading was related to the back pressure in a standardized manner. The back pressure for the filter prepared for this test was measured at 30.7 in of water, well in excess of the soot loading specified for safe regeneration (20 inches

of water back pressure).

In final preparation for the test, the engine was carefully set to the prescribed 700 rpm idle. Several minutes passed while temperature transients worked their way out of the engine and exhaust system. When we were confident that the engine had reached fully steady-state operation, measurements were taken of all system parameters.

The engine inlet air flow-rate was measured at 275 lb/h (3.75 inches of water on calibrated manometer), only 2/3 the design flow. The raw exhaust gas temperature was 334 deg F (168 deg C), slightly higher than had been anticipated (320 deg F). The fuel flow to the engine was 1/8 litre in 3 minutes, 39 seconds (aprox. 4 lb/h). The carbon monoxide concentration in the exhaust gases upstream of the filter was 45 ppm while downstream of the filter it was about 100 ppm which would seem to indicate that there is always some small amount of regeneration taking place.

Finally, the gas temperatures measured within the filter casing itself were 239 deg F in the inlet cone and 170 deg F in the outlet cone. The heat loss between the exhaust manifold and the filter inlet was aproximately 6270 btu/h; that between the filter inlet and outlet aproximately 4550 btu/h.

With everything checked and the system evidently in the steady state, the heater unit was switched on. The progression of events is shown in figure 2.2 - E.

The filter inlet gas temperature rose steadily at an average rate of 2.8 deg F per second. The CO monitor had been switched to measure only the downstream (of the filter) concentration, an indicator of the onset of regeneration. As the filter inlet temperature rose, the CO reading climbed slowly. About when the filter inlet temperature reached the expected regeneration temperature (3-1/2 minutes from switching the heater on), the CO reading quite suddenly began to climb dramatically. After rapidly switching through three progressively wider ranges on the monitor, the reading was lost to the monitor's maximum of 5000 ppm. Still, there was no sign of any temperature rise at all downstream of the filter.

When the filter inlet temperature reached 1200 deg F (in aproximately 5 min. 40 seconds from starting the heater) all banks of the heater were switched off. There was some concern that the CO reading might be erroneous or else the thermocouples measuring downstream temperatures themselves might be malfunctioning.

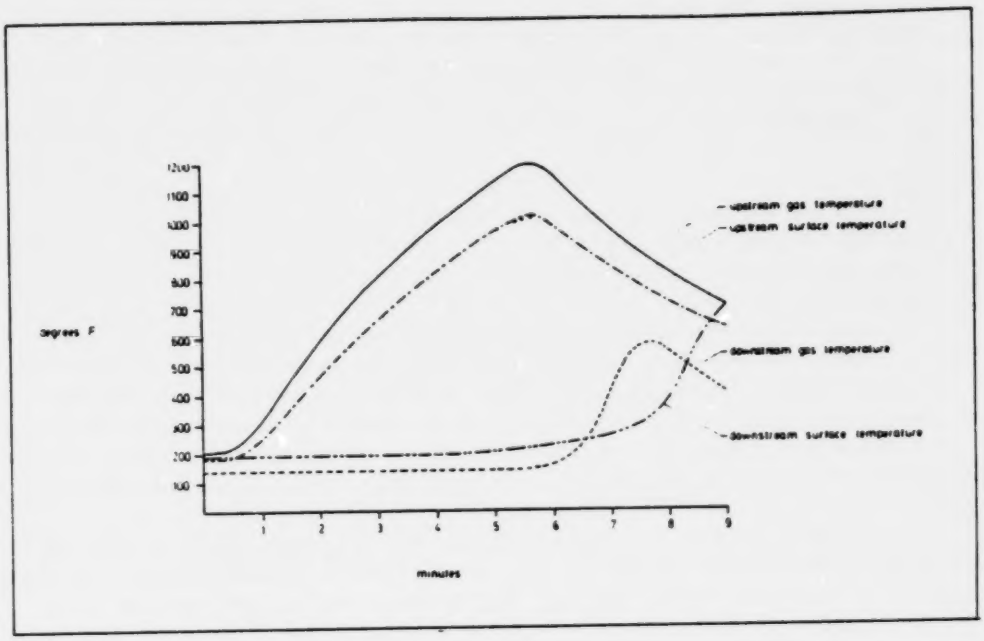

Figure 2.2 - D

Prototype II - First Trial

Then, as the filter inlet gas temperatures began to fall (with the heater off), the filter outlet gas temperature finally began to climb, confirming that regeneration had indeed been induced. The observed upward climb began fully six minutes into the experiment, and a little more than two minutes after the CO readings had indicated that regeneration was taking place. The filter outlet gas temperature peaked at 570 deg F, in about 90 seconds, and then began to fall.

The temperature rise shown at the filter outlet surface lagged that of the outlet gas substantially as well. This temperature, which was actually measured upstream of that of the outlet gas, did not begin to rise appreciably until the gas temperature had begun to fall. This would appear to indicate that the regeneration induced by this system tends to be concentrated in a small number of passages of the filter spreading across the cross-section rather

slowly. The gas temperature at the filter outlet never exceeded 570 deg F (due to the mixing of flows from unstarted, regenerating and regenerated channels) while the surface temperature at the point measured ultimately rose to 1250 deg F. This gives an idea of what magnitude of temperatures may be attained locally while the regeneration proceeds in what appears to be a very controlled process.

From start to finish, the regeneration of the filter took about 10 minutes using the second prototype powered by welders (giving the full 24 V across the heater). The maximum filter surface temperature measured was 1250 deg F and the filter inlet gas temperature achieved by the heater was 1200 deg F. The heater was turned off before it reached its peak input. These temperatures were probably attainable by this heater, designed only to reach 950 deg F, because of the much lower than expected exhaust gas flow rate encountered at the 700 rpm idle.

The next major test of the system was its use under battery power rather than with welders. The welders were removed from the system and the battery pack installed as shown in figure 2.2 - D. The filter used this time had been loaded to give 20 inches of water pressure drop at engine operation of 2200 rpm and 150 ft.lb torque.

The sequence of preparation for regeneration was followed as in the first trial. The engine was set to 700 rpm and idled there till transients had disappeared. Before closing the power circuits, the terminal voltage of the battery pack was measured at 25.5 volts.

To make a long story short, under conditions completely similar to those of the first trials, the battery powered unit failed to regenerate the filter. Upon closing the circuit, the terminal voltage immediately fell to 19.8 volts, the result of an unexpectadly high internal resistance in the battery pack itself.

At that voltage, the current passing through the rods was only 840-850 amps. With the total resistance of the heater unit being 0.024 ohms, the input power was a maximum 16.9 kW. This was about 70% of the power of the unit operating at 24 volts. Given the performance of the heater in the first trial, we would expect a temperature rise of no more than 620 deg F. From the 320 deg F exhaust gas temperature, this would have given a filter inlet temperature of only 940 deg F. At that level, regeneration was possible, but not probable. Unfortunately, there was another

factor which reduced that possibility even more.

At the rate of discharge experienced, the battery pack's terminal voltage decayed rather quickly. Within two minutes, that decay was a full volt. This reduced the current through the heater by a further 40 amps. That had the effect of further reducing the input power by about 800 Watts. By the time that the thermal inertia of the system had been overcome, the input power was no longer sufficient to achieve the needed temperature rise.

Thermal inertia had proven to be another major stumbling block. In the first trial, it had taken three and one half minutes to reach regeneration temperature, even with full power. Doubtless, a good portion of that delay was attributable to the heat absorption of the heater shell. Nevertheless, during the set-up of the test, we had noticed that the rods themselves took at least two minutes to "come to colour." This observation prompted us to speculate that the rods themselves might be too thermally heavy for the application.

In an investigation of this, subsequent to these tests, we determined that this was indeed the case. The MgO packing material of the rods is an excellant conductor. Unfortunately, it has a rather large heat capacity as well (10.86 Btu/lb.F for MgO compared to 0.12 Btu/lb.F for the Incalloy sheathing or the actual conductor). This, in fact, is why it is used. It tends to absorb and distribute the heat from the conductor very well. The heat capacity of this material would appear to be the major delay in achieving light-off. If each of these rods were surrounded by a perfect insulator, it would still take about 80 seconds for the sheath to reach 950 deg F at the full power rating.

It might have been possible to achieve regeneration had we added a third pair of series connected batteries to the battery pack. Using network analysis, with the battery performance data gathered in this testing, it was determined that each battery's internal resistance was 0.00636 ohms. In the particular configuration used here, the internal resistance of the entire battery pack was the same as that of the individual batteries. By the voltage divider principle, a significant portion of the batteries' cell voltage was wasted on their own internal resistance. This is why only 19.8 volts appeared on the pack's terminals; and also why the current was limited to 840 amps.

A third pair of series connected batteries, added to the origional two pairs, would have reduced the effective internal resitance by one third to 0.00424 ohms. This, in turn, would have increased the voltage

across the heater to 21.7 volts, giving a circuit current of roughly 900 amps and a heater power of 19.6 kW. Again judging by the heater's performance in the first trial, this would have given a temperature rise to 1040 deg F, sufficient for regeneration to occur. Because the current in each individual pair of batteries would be reduced from 420 amps to 300 amps, the rate of voltage decay would have been slowed, allowing some time to overcome the system's own thermal inertia.

A second option would have been to reduce the overall resistance of the heater to better match the now known battery characteristic. An overall heater resistance of 0.0105 ohms instead of 0.024 ohms would have, initially at least, given a circuit current of about 1500 amps. At this current, the power in the heater would have been 24 kW immediately on closing the circuit. Unfortunately, due to the higher current load (750 amps as opposed to 420) the voltage decay of the batteries would have been much faster than we observed in the second trial. We would most assuredly be caught again by the thermal inertia problem.

Finally, this series of tests has brought to the fore the problem of using conventional type heating elements in an application such as this. That problem, it is re-iterated, is the problem of thermal inertia. Conventional heating elements are designed conservatively to have both a low surface watt density and a high amount of thermal "buffering". A less conservative design for heating elements can eliminate those factors, thereby reducing the thermal inertia, but that is not done without its risks. To be sure, the indication from this test is that a bare conductor design could reduce the heat-up time from minutes to seconds. Such a reduction would substantially ease the power supply problem as the rate of discharge of a battery is limited only by the battery's internal resistance and time. If we could be certain that the heater would only be operated for periods of a few seconds at a time, it is quite possible to get current ratings ranging in the the thousand amp and up vicinity from simple and compact battery packs. This problem is dealt with in the next section of this report.

3 Conclusions

The first conclusion we have drawn from this work is that the filter is not as "delicate" as we had origionally thought it to be. A fair amount of the effort in this project has gone into avoidance of certain conditions during the regeneration. Low flow regeneration, high exhaust gas oxygen content, thermal gradients within the filter monolith, etc., etc. were all things which we had been cautioned to avoid, either directly by the manufacturer, or in the reading of the several papers published on the matter. The first prototype, a failure, was a studied attempt to meet all of these cautions. These are all legitimate concerns, but perhaps the whole issue is a little overstated.

Through the course of this project, and with information derived from parallel work done by CANMET, we have found that the particular filter geometry used can safely be regenerated over a wide range of conditions. One of the filters used has been regenerated using the auto-regenerative process at one extreme and with a very low-speed induced regeneration at the other. In the former case, regeneration took place at very high exhaust gas flow and temperature and very low exhaust gas oxygen content, because of the engine loading. In the latter case, the oxygen content was very high and the flow and temperature low because the engine was at a low speed idle. There was no apparent damage caused the filter by either process. Of course, these trials cannot be considered exhaustive, but they might be considered indicative of a fair amount of leeway in the design of an onboard regeneration system.

The second major conclusion is that an onboard regeneration system is feasible and should be based on the following design principles:

i) Minimiztion of the overall power requirement by minimizing the exhaust gas flow at which the regeneration takes place. A low speed idle gives the minimum exhaust gas flow for a completely on-board regeneration process. It appears that the low flow and high oxygen content donnot have a harmful effect on the filter during regeneration.

ii) Confine external heat input strictly to the time required to initiate the regeneration. The regeneration process is self sustaining once initiated, even at the low filter inlet temperatures of an idling engine.

iii) Thermal inertia is an important consideration. Given the thermodynamic requirements of getting the temperature up to ignition levels, power draw will be high. Reasonably sized and priced batteries will be pressed to supply the current required. Conventional heating elements have a very high thermal inertia due to the conservative policy of providing heat distribution enhancing materials between the actual conductor and a containing sheath. A bare conductor type heating element(s) will reduce the thermal inertia time delay, from start-up to light-off, by a very large factor. This will allow considerably higher current ratings for a given battery because of the much shorter time of discharge.

Of those three design criteria, the first two are met by the presently supplied units. These units do employ conventional elements, and so their thermal inertia is not what it might be. Nevertheless, they are functioning models, and with the extra batteries suggested, they will work quite well. Battery life might be less than desireable.

In the design of a bare conductor regeneration heater unit, the conservatism of the conventioal system must be left behind. To assure that the thing won't burn out the second time fired, or be eroded to uselessness within a week, a fair amount of consideration must be given the following factors:

i) Electrical integrity and safety of the unit operating in a harsh environment with exposed conductors.

ii) Corrosion of the conductors in the moist gases.

iii) Erosion of the conductors by the very particulate matter being controlled.

iv) Pressure drop within the unit as a result of the extended conductor surface area, required to reduce surface watt densities to acceptable levels.

Once all of those issues have been addressed, we are confident that a low-inertia regeneration heater system could be developed and would, indeed, be practical.

4 Recommendations

1) Field test the second prototype with a battery pack as specified in this report. Test for deliterious long term effects of regeneration, using the gas heating principle, on the filter.

2) Field test a third prototype, one not tested within this project, but based on the radiant heating principle. This principle has not met with all-round approval because of high expected thermal gradients, but one has been supplied nonetheless for testing. Figure 4.1 - A shows its implementation.

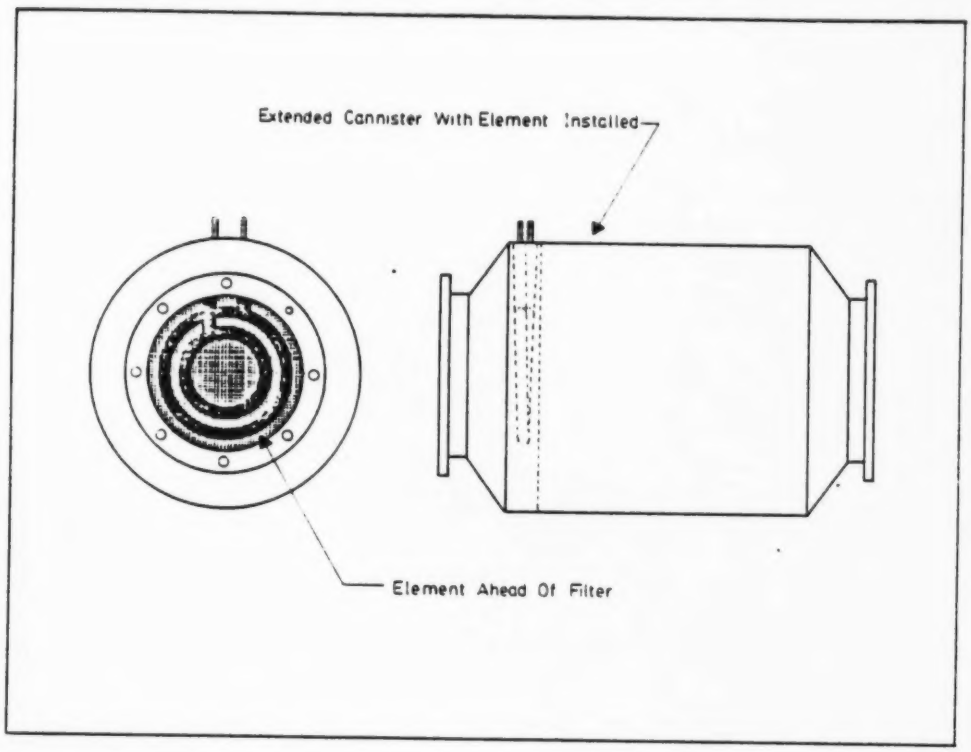

Figure 4.1 - A

The Radiant Option

3) Support the development of a true low-inertia regeneration system, based on the gas heating principle, by provision of test facilities and guidance through regulatory requirements.

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Appendix A

Cost Estimates

A) Vehicle Equipment For Shore Powered System

.Heater unit for Deutz F6L 912 W.....$2600
engine or per manifold for
equivalent gas flow

.Vehicle temperature control and..... 210
alarm

.Vehicle back pressure alarm..... 140

Total.....$2950

B) Vehicle Equipment For Self-Contained System

.Modifications and upgrade of existing.....$1000
vehicle battery pack and re-charge
system

.As A) above..... 2950

Total.....$3950

C) Fixed Shore Power Regeneration Station

.220 V outlet wired in.....$2100

.CO monitor & fan..... 3800

Total.....$5900

D) Mobile Shore Power Regeneration Station

.Battery.....$4121

.Battery Trailer..... 1200

.Battery Charger..... 2000

Total.....$7321

Appendix B

Design Drawings

Appendix C

Installation Drawings

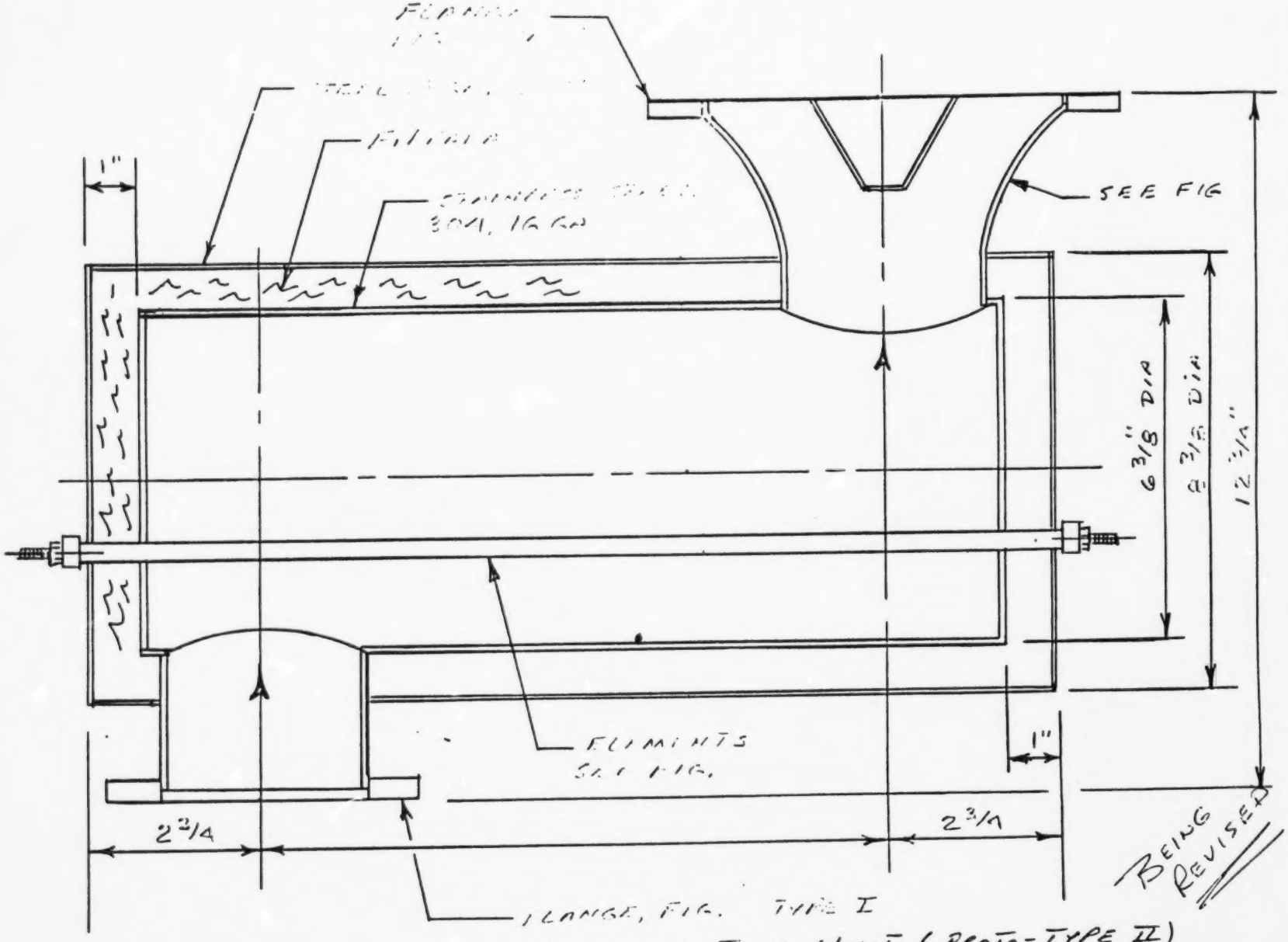


FIG. 21

FLANGE, FIG. TYPE I

REGENERATION UNIT (PROTO-TYPE II)

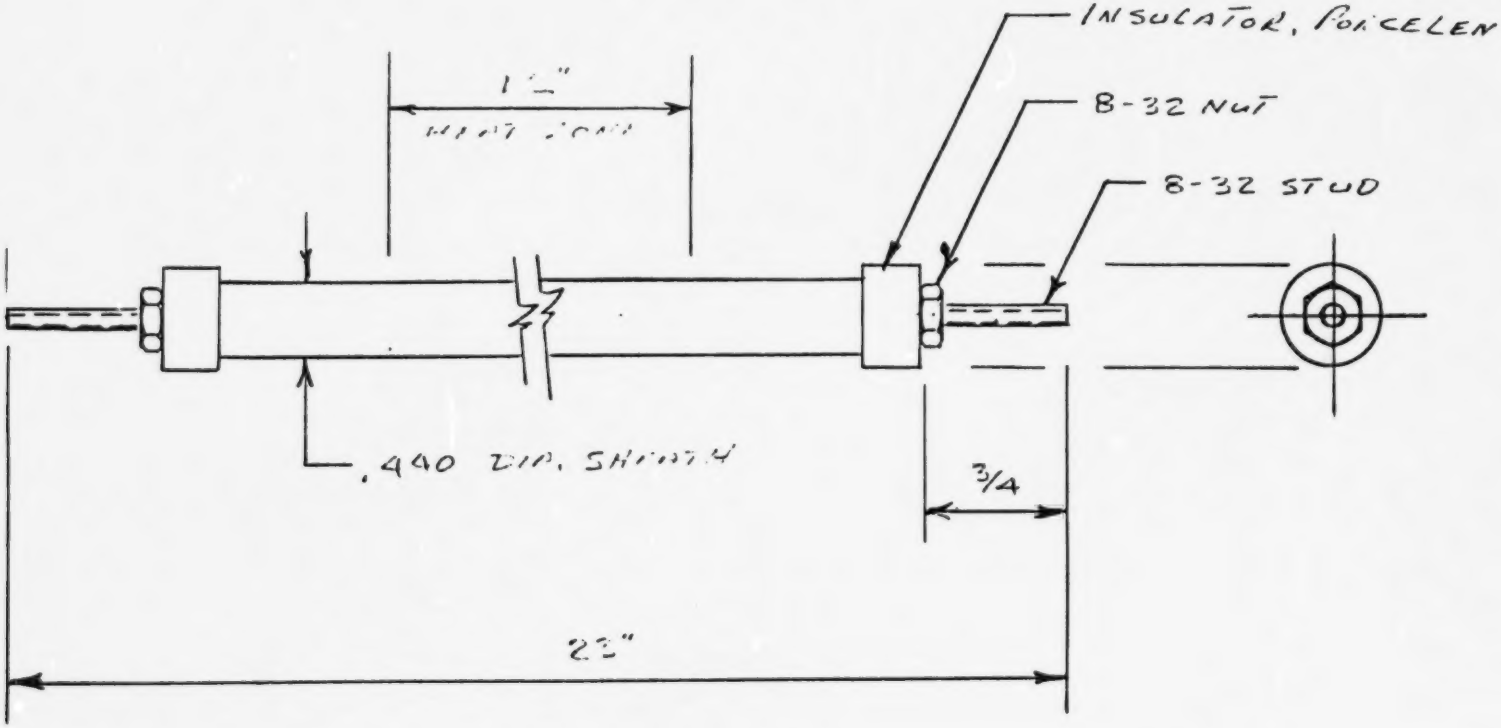
FIGURE

11X17 PRINTED ON NO. 1000H CLEARPRINT

PRINTED ON NO. 1000H CLEARPRINT 11X17

FIG

FIGURE



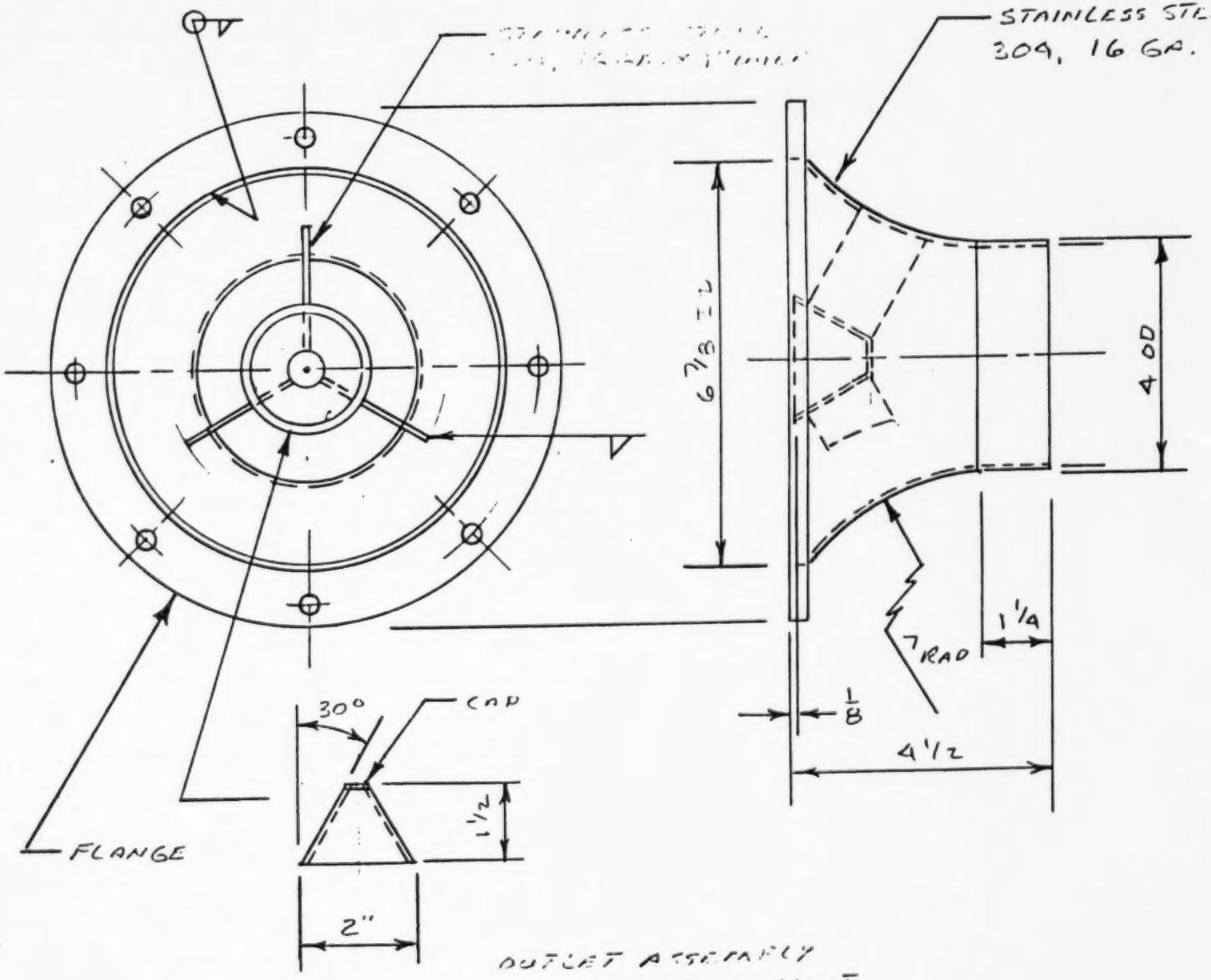
RATING 24 VOLT
22.2 AMP.

UNITS REQUIRED FOR
REGENERATION UNIT
DESCRIBED --- 45

HEATER ELEMENT

FIGURE

11E17 PRINTED ON KO. 1000H CLEARPRINT



OUTLET ASSEMBLY
[illegible] UNIT

FIGURE

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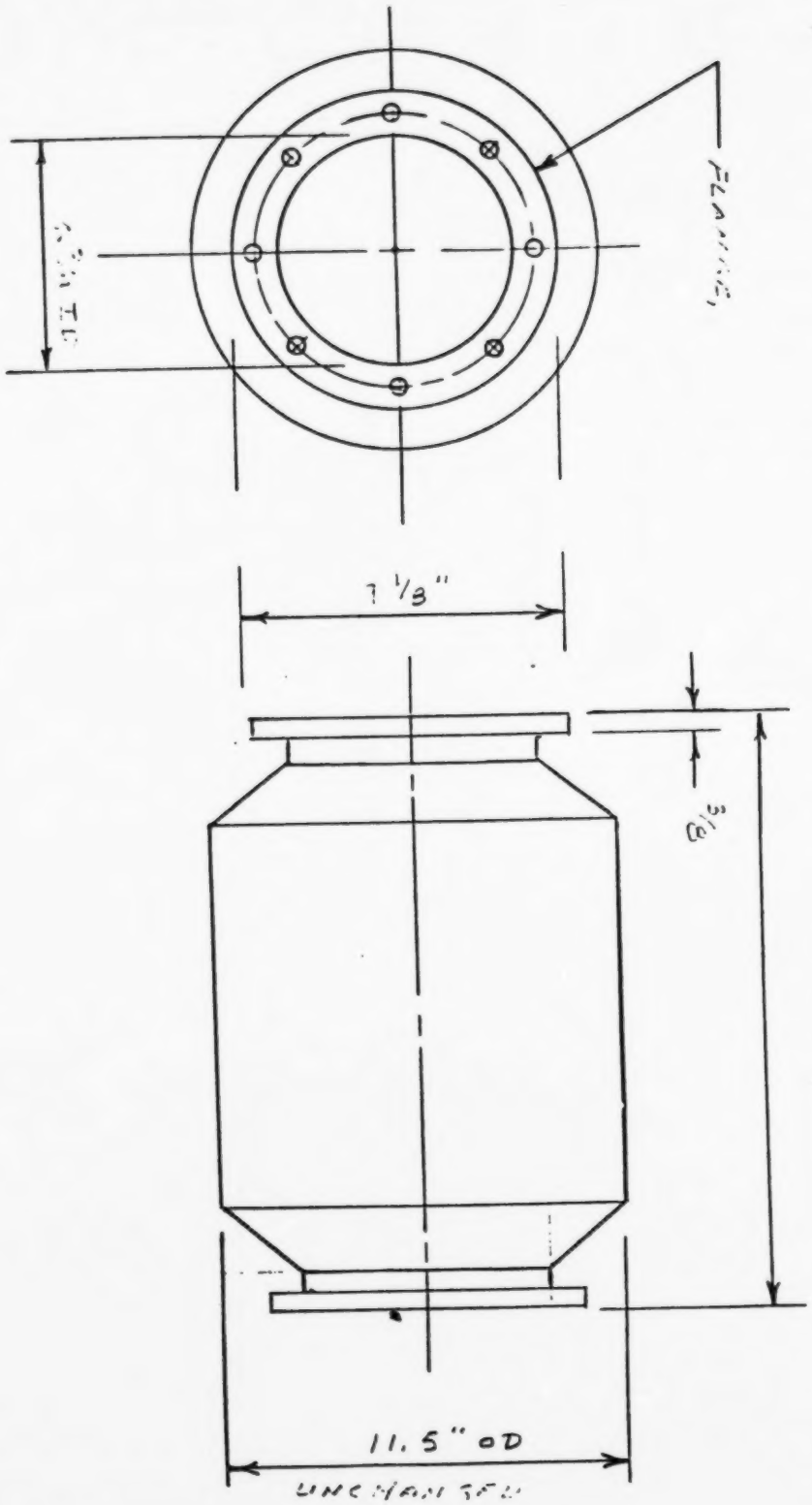
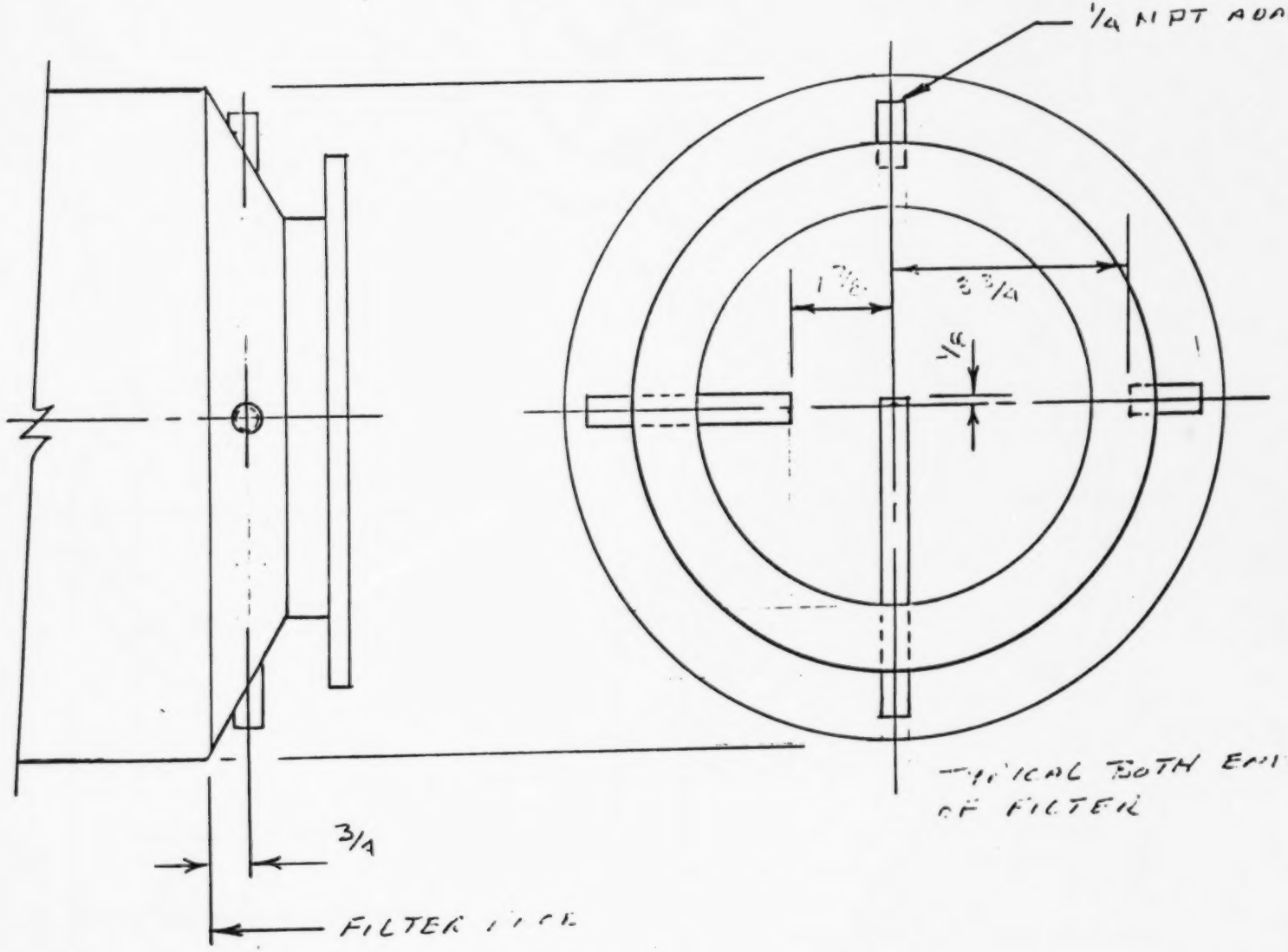


MANIFOLD FLOATER
FIGURE 2



...ACCORDANCE WITH ... ATIONS
MODIFIED FILTER

FIGURE

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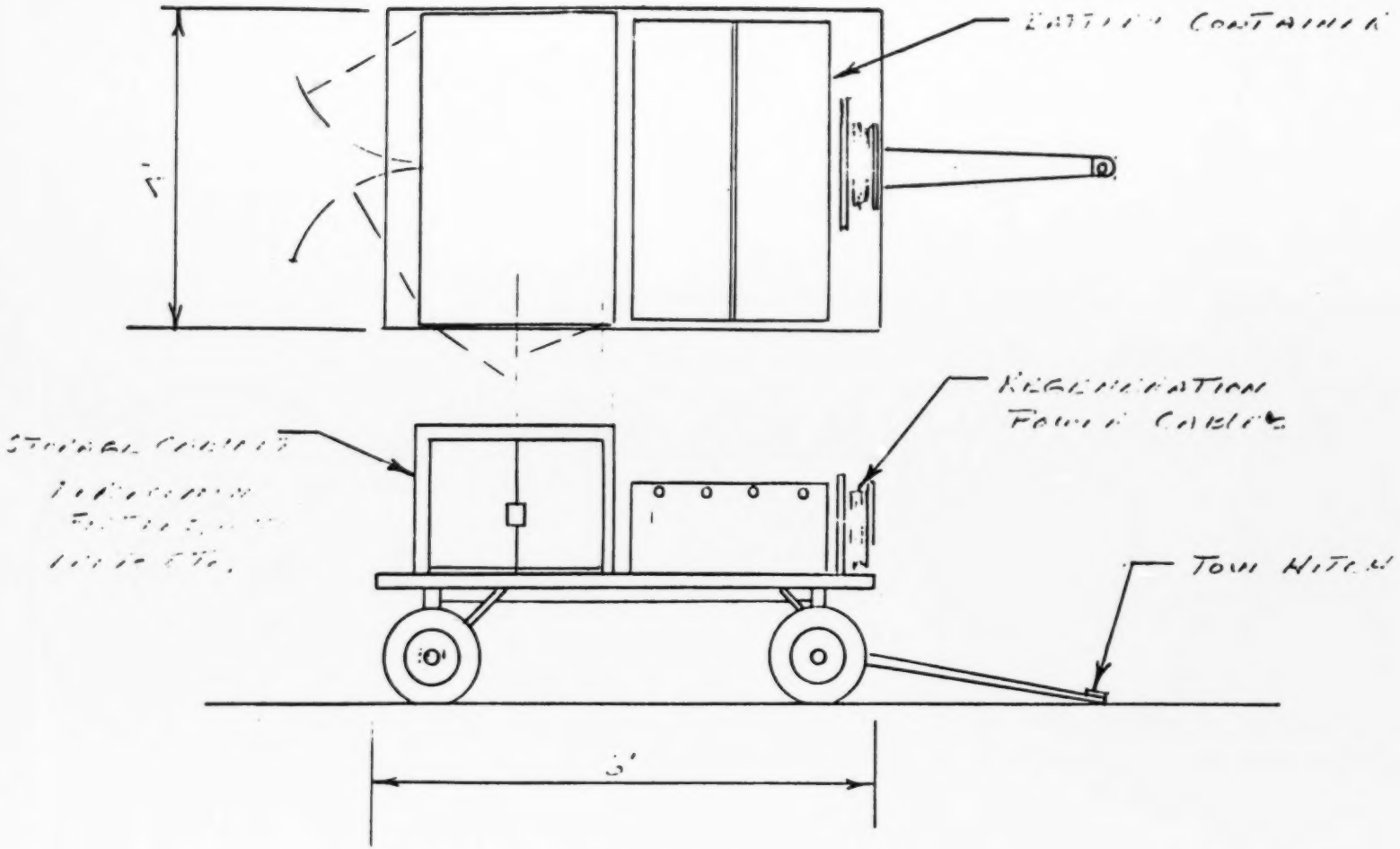
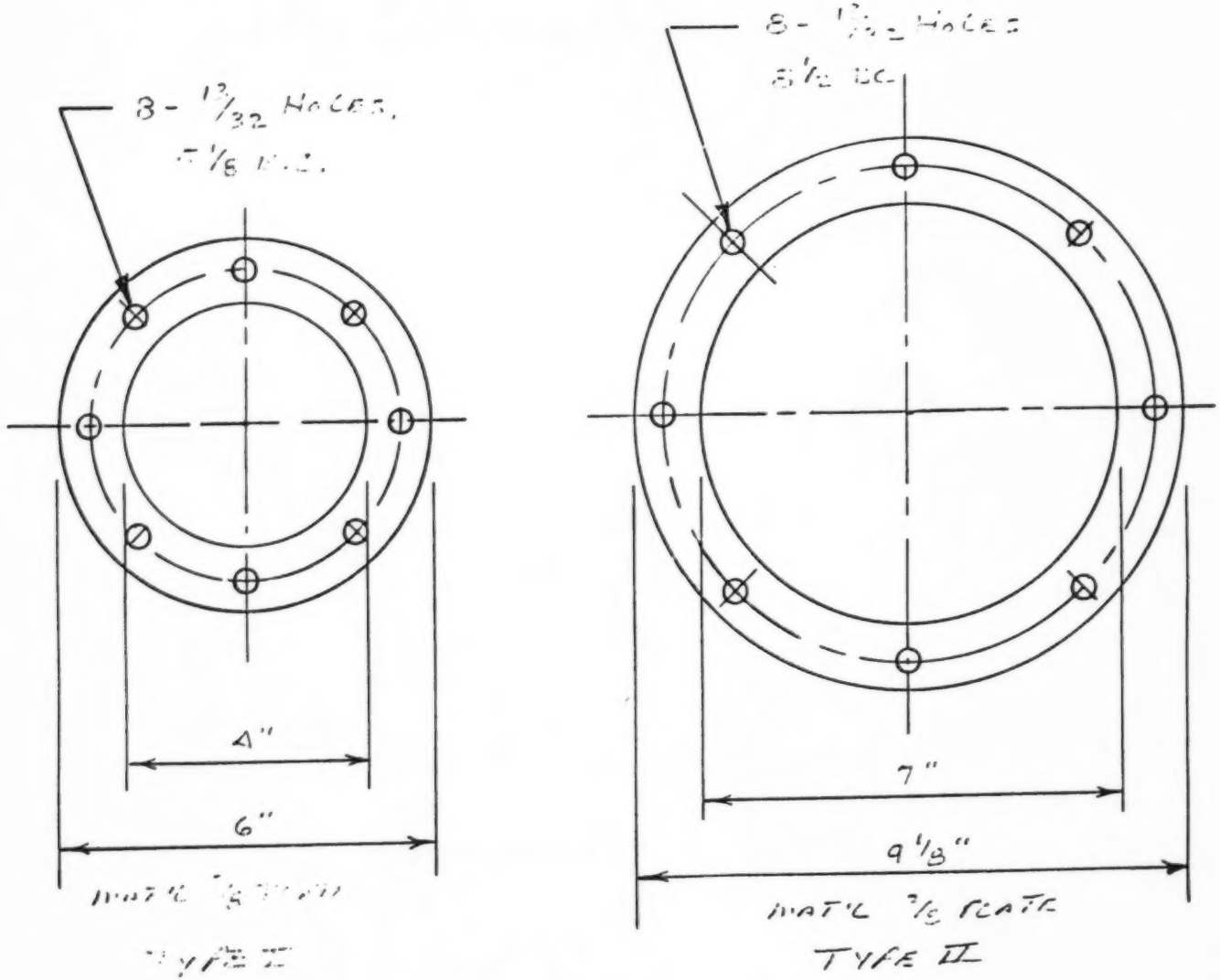


11X17 PRINTED ON HQ 1000H CLEARPRINT



FLANGE CONFIGURATION

FIGURE

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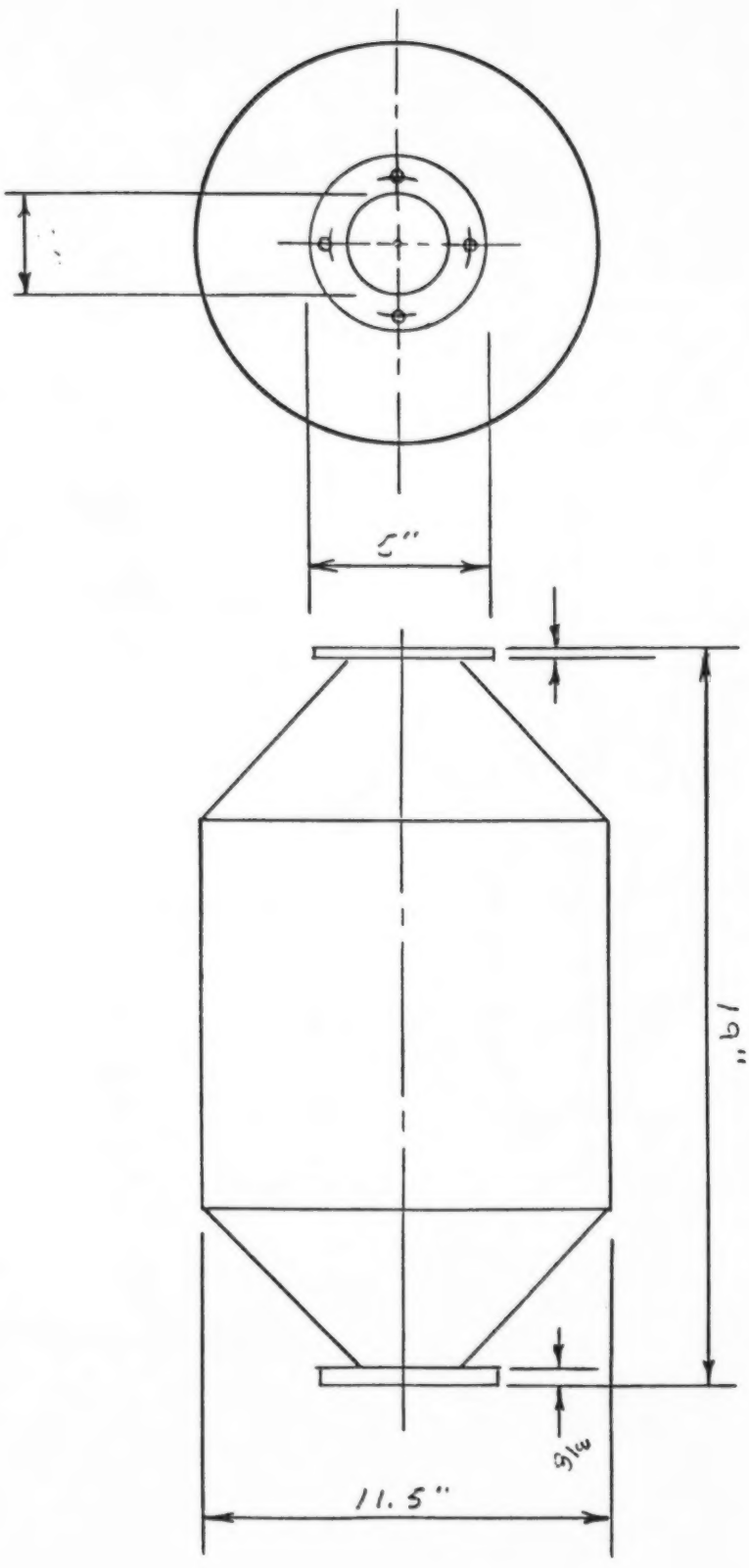
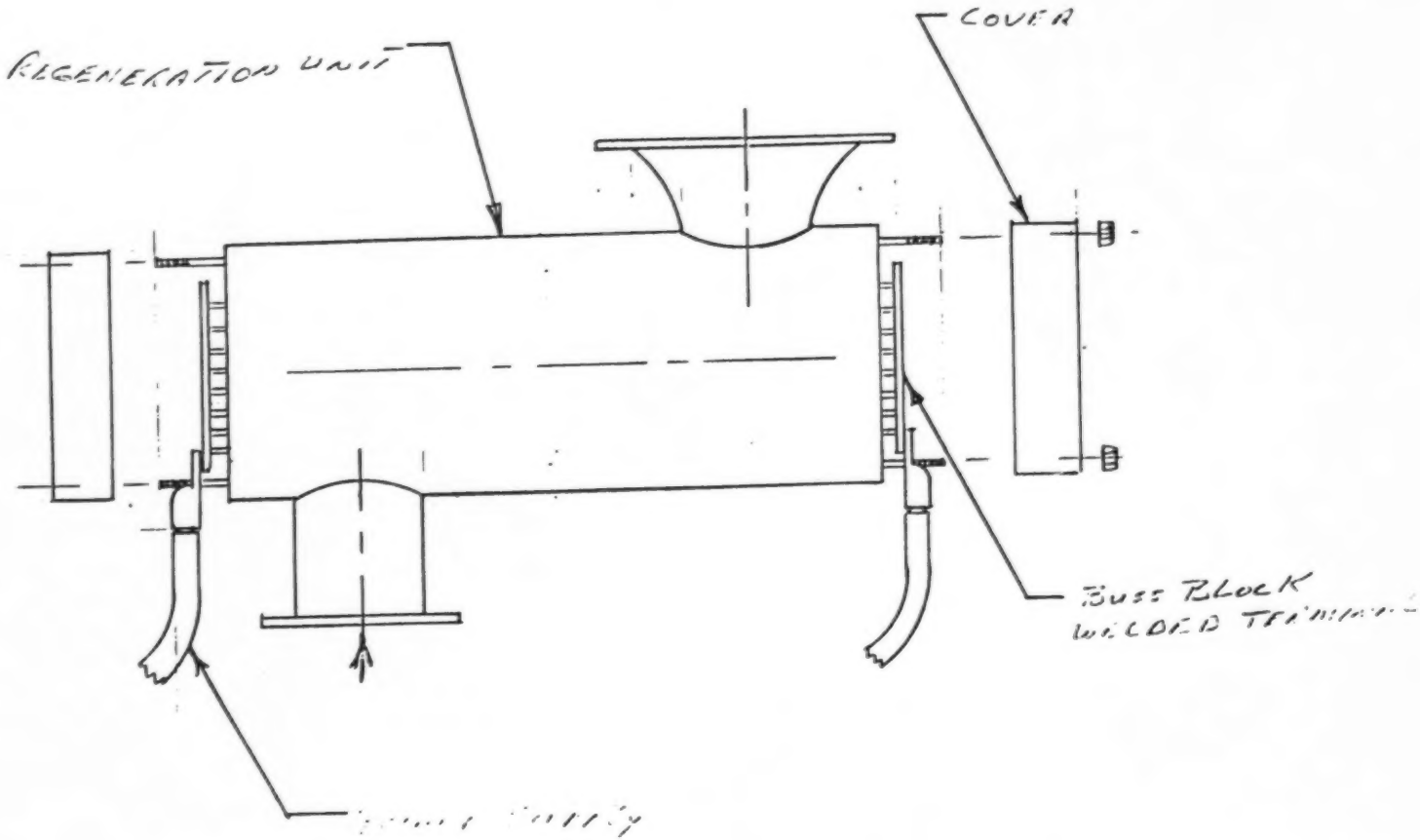


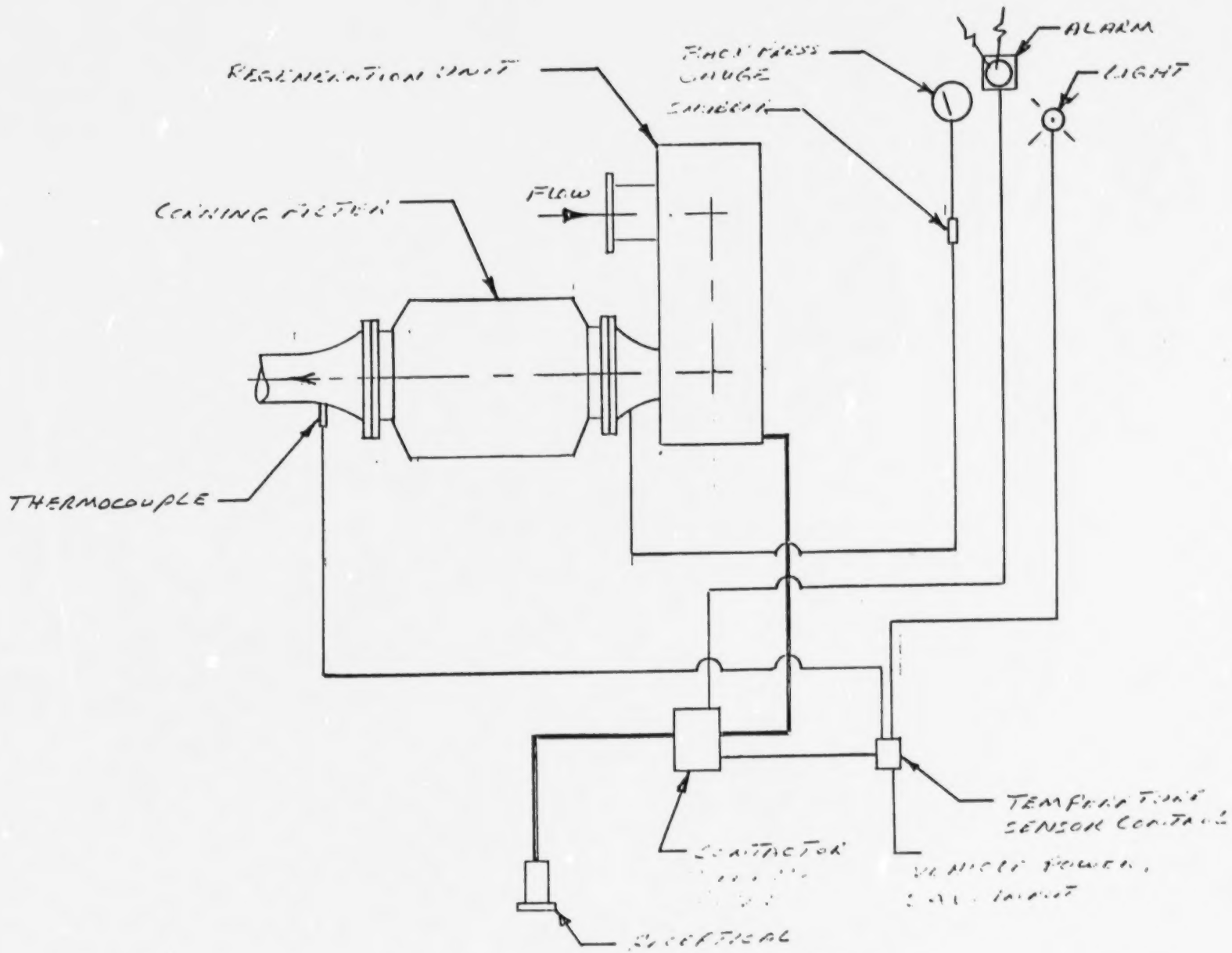
11X17 PRINTED ON NO. 1000H CLEARPRINT



FIGURE

11217 PRINTED ON NO. 100GH CLEARPRINT

11X17 PRINTED ON NO. 1000H CLEARPRINT



SILICA POWER REGENERATION VEHICLE CIRCUIT

FIG 1A

11X17 PRINTED ON NO. 1000H CLEARPRINT

FIG. 1

FIG. 2, FLANGE TYPE II

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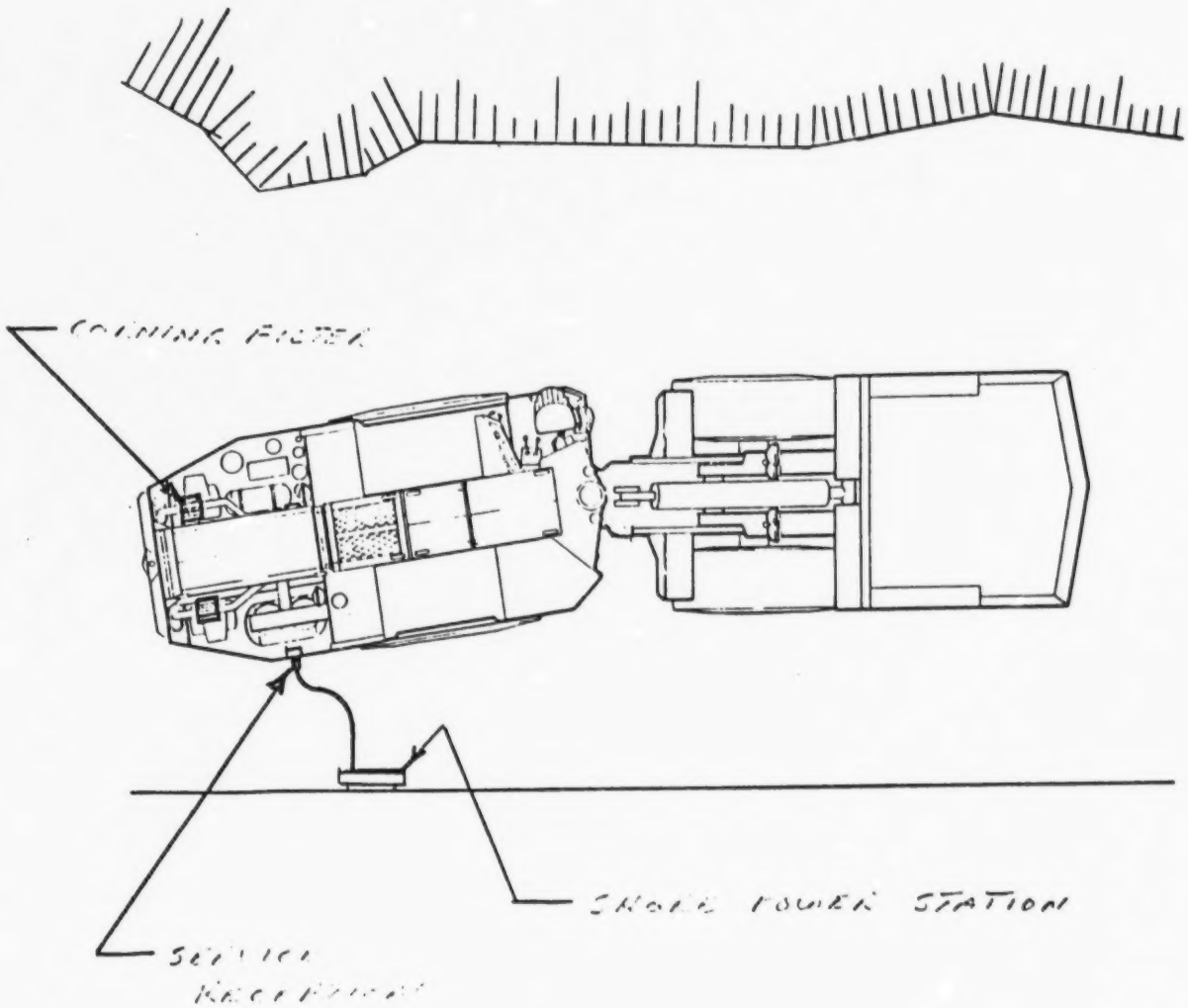

SOLAR POWER SATELLITE

SOLAR POWER REGENERATION

SOLAR POWER REGENERATION
REGENERATION RAY

FIGURE

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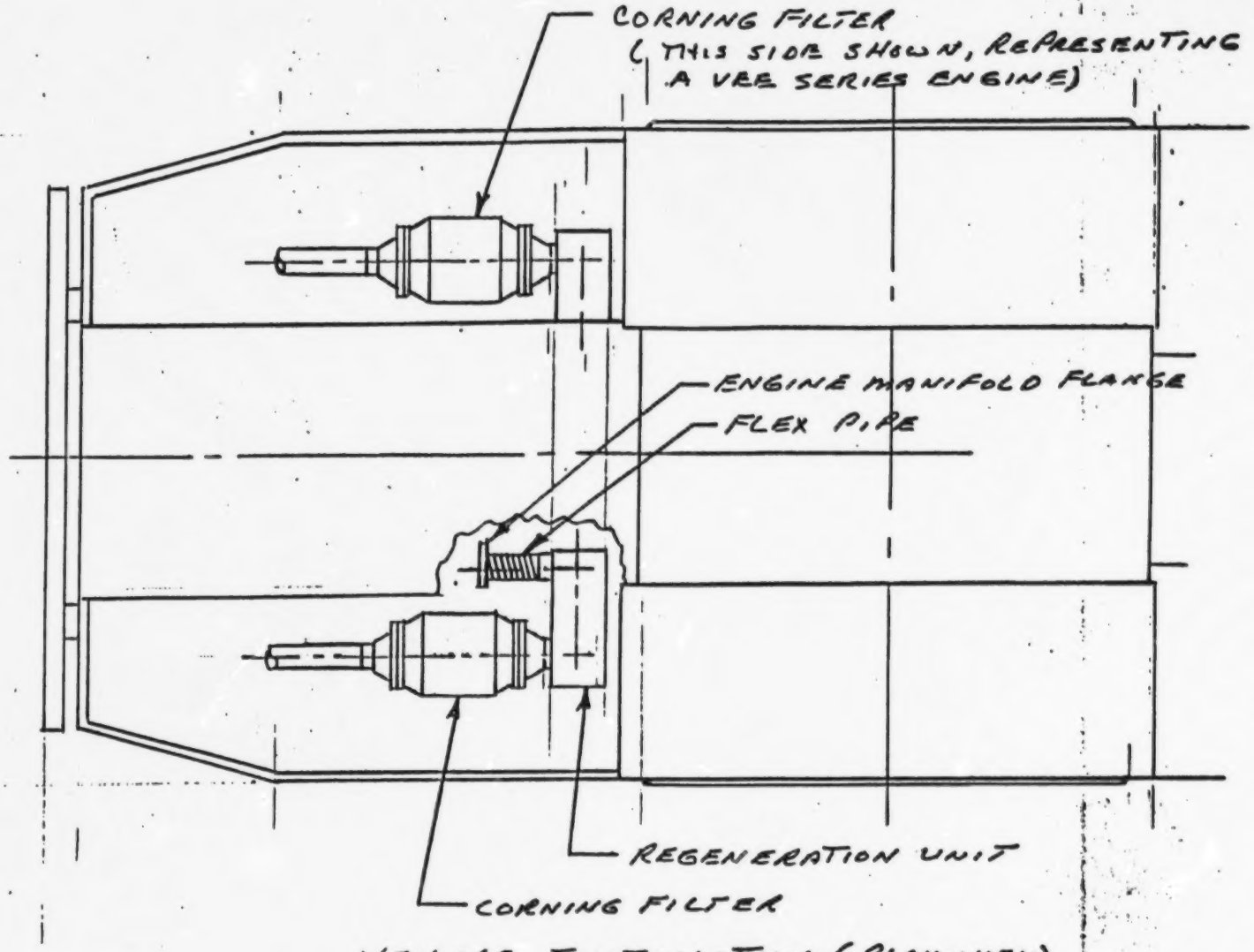

FIG.

VENICLE INSTALLATION (PLAN-VIEW)
(SCOOP TRAM)

FIGURE

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POOR

QUALITY

ORIGINAL